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ORIGINAL PAPER

Climatic variations explain annual fluctuations in French Périgord black truffle wholesale markets but do not explain the decrease in black truffle production over the last 48 years

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Abstract Production of the black truffle (*Tuber melanosporum* Vittad.) has experienced a decline in France over the last century. Different sociological factors as well as climate change have been suggested as possible explanations for this decline. The aims of this study were to assess the effects of annual climatic variations on black truffle sales by analysing reliable data. Over the past 25 years, almost 90 % of French truffle sales occurred in the southeastern region of France and, despite a decrease in southwestern France, for the last 25 years, sales were stable for France as a whole. An analysis of the two main southeastern wholesale markets (Richerenches and Carpentras) revealed that the main factor explaining the huge annual variations was the cumulative hydric balance from May to August of the year *n*. For the first time, frost days were also identified as an important factor in Richerenches. Using the model established for the past 25 years and the climatic data for the Richerenches and Carpentras basins, the truffle sales would have been stable from 1965 to nowadays. This simulation suggested that the production decline observed since 48 years could be attributed more to the change of rural world than to the climatic changes. The stability of production or the slight increase observed during the last 25 years could reflect the input of truffle orchards recently planted.

Keywords Périgord truffle · France · Weather variations · Climate changes · Simulation

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Introduction

The Périgord black truffle (*Tuber melanosporum* Vittad.), a fungus belonging to Ascomycota, is one of the most famous edible mushrooms. This ectomycorrhizal fungus was first cultivated in the middle of the nineteenth century in France, Italy and Spain in association with its hosts, which were mainly oak trees. In France, Périgord black truffle orchards are now managed ecosystems. In recent years, plantations have proliferated outside Europe. In Australia and New Zealand, several truffle orchards have begun to produce ascocarps. However, Europe continues to contribute more than 95 % of the total worldwide production of truffles.

Previous studies have shown that the production of the Périgord black truffle has steadily decreased in France since the beginning of the twentieth century (Callot et al. 1999; Olivier et al. 2012; Büntgen et al. 2012a, b). Following the phylloxera crisis of the 1870s, many vineyards were reconverted into truffle orchards. At that time, sheep grazing was extensive and left open spaces that created favourable

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conditions for truffle production. The apex of French truffle production was reached at the beginning of the twentieth century with a record of approximately 1,000 tons in 1904; in recent years, annual truffle production has not exceeded 30–50 tons. The decline of truffle production has been attributed to several causes. The first is rural desertification, which led to a decrease in the surface of land devoted to truffle cultivation. Furthermore, the remaining truffle orchards were no longer managed, and the canopy gradually closed, which decreased water availability and led to the disappearance of truffles. The success of the mass production of quality mycorrhizal seedlings with *T. melanosporum* has led to an increase in planted surface since the 1980s (Chevalier and Grente 1978; Chevalier 1998). In France alone, 800 to 1,000 hectares of plantations have been established annually over the past 20 years; however, these efforts have not allowed truffle production to reach the level of production achieved at the beginning of the twentieth century.

Climate change, which increases summer hydric stress and potential evapotranspiration, is also believed to have contributed to a decline in truffle production (Büntgen et al. 2012a, b). In recent years, truffle producers have tried to overcome climatic stresses in truffle orchards by using technical management methods, including tree pruning, soil tilling and watering.

The negative effects of dryness on truffle production are well known. In 1914, Pradel (1914) suggested that water supply could enhance truffle production during summer droughts. Le Tacon et al. (1982) demonstrated that maintaining soil pF under 3.5 during summer months through watering greatly increased ascocarp production. These results were confirmed by Carbajo et al. (1999) and later by other authors.

Annual climatic conditions affect different stages of the truffle life cycle, which starts in late winter or in spring with the germination of haploid spores released by mature ascocarps and the colonization of tree roots by haploid mycelium to form ectomycorrhizal symbiotic associations (Paolocci et al. 2006; Riccioni et al. 2008). The young truffle, born in the late spring from the ectomycorrhizas, grows slowly during the summer months and starts to become mature in November. Crops in southern France generally start in the middle of November and finish in the middle of March the following year. This long life cycle makes the truffle harvest sensitive to climatic conditions throughout the entire year and particularly sensitive to water balance during the summer months, often very negative in the Mediterranean climate.

Frost is another climatic factor often reported by truffle growers to have a negative effect on truffle production; it is common some years, following frost periods, to find more than 50 % of the ascocarps frozen, rendering them unsuitable for the fresh wholesale market; they are accepted as only suitable for canned “brisures”. To our knowledge, the effect of frost on truffle production has not yet been investigated in published studies.

The objectives of this study were to determine the following:

1. Whether annual climatic conditions (i.e. drought and frost) have an effect over the past 25 years on truffle production despite the intensification of cultivation methods.
2. Whether climate change could explain the decrease of the French truffle production observed from 1964 to 2013.

Materials and methods

Data from the truffle wholesale markets

Data are published weekly by the “Réseau des Nouvelles des Marchés” of the French Ministry of Agriculture (http://www.snm.franceagrimer.fr/). At the end of the week for the eight weekly markets in southwestern and southeastern France, the quantity of black truffles (*T. melanosporum* and *Tuber brumale* ascocarps) sold is estimated by collecting data (weight of fresh truffle sold by each merchant or trader) sourced directly from vendors (Table 1; Fig. 1). *T. brumale* ascocarps represent on average 5 % of the total sales. While there has been no collation of invoices performed, these estimations are the most reliable data available to date.

Five markets (Richerenches, Valréas, Carpentras, Aups and Montagnac-Montpezat) are situated in southeastern France and three (Lalbenque, Sarlat and Jarnac) are situated in southwestern France. Sales data were recorded from 1988 to 2013 in Richerenches, Valréas and Carpentras, from 1990 to 2003 in Aups and 2003 to 2013 in Montagnac-Montpezat. For the three southwestern markets, we have data from 1988 to 2013 for Lalbenque, from 2009 to 2013 for Sarlat and from 2013 for Jarnac (Table 1). The quantity of truffles sold in these markets reflects the rate of local production, although occasionally, particularly for Richerenches, additional external contributions from neighbouring regions or countries are factored. In addition, all truffles are not sold through these markets; more than half (on average 55 % in the period 1988–2013) are sold directly to traders and resellers before reaching the market or are consumed locally. The estimation of the total French truffle production, published in guide books (Callot et al. 1999; Olivier et al. 2012) and in Büntgen et al. (2012a), are partially based on these data, so it is not surprising that a significant Pearson correlation (R^2=0.73, P<0.01) exists between the wholesale markets and the total French truffle production as estimated by the Fédération Française des Trufficulteurs (Fig. 2a).

Table 1 Sales of the eight French black truffle wholesale markets from 1988 to 2013 expressed in tons

Year	Southeast	Southwest	Total	Richerenches (SE)	Carpentras (SE)	Valréas (SE)	Aups (SE)	Montagnac-Montpezat (SE)	Lalbenque (SW)	Jarnac (SW)	Sarlat (SW)
1988/89	11.3	2.505	13.805	6.78	2.22	2.3			2.505		
1989/90	3.704	1.41	5.114	2.455	0.737	0.512			1.41		
1990/91	5.8	0.93	6.73	1.87	1.36	0.43	2.14		0.93		
1991/92	8.663	2.665	11.328	5.72	1.67	0.888	0.385		2.665		
1992/93	13.435	3.708	17.143	6.36	4.785	1.41	0.88		3.708		
1993/94	7.54	5.471	13.011	4.26	2.455	0.468	0.357		5.471		
1994/95	7.833	1.122	8.955	4.36	2.35	0.363	0.76		1.122		
1995/96	9.324	1.89	11.214	5.205	2.395	0.344	1.38		1.89		
1996/97	23.152	1.186	24.338	13.27	7.33	0.842	1.71		1.023		
1997/98	15.076	5.283	20.359	10.62	2.81	0.841	0.805		5.283		
1998/99	9.165	0.6	9.765	6.44	2.425	–	0.3		0.6		
1999/00	19.105	1.665	20.77	13.15	4.45	0.8	0.685		1.665		
2000/01	15.862	1.017	16.879	11.609	2.88	0.848	0.525		1.017		
2001/02	7.87	1.483	9.353	6.05	1.315	0.25	0.255		1.483		
2002/03	16.499	1.885	18.384	9.835	4.95	0.434	1.28		1.885		
2003/04	3.691	0.166	3.857	2.87	0.566	0.089		0.166	0.166		
2004/05	6.459	1.008	7.467	3.8	1.898	0.145		0.616	1.008		
2005/06	4.945	1.819	6.764	3.395	0.924	0.123		0.503	1.72		
2006/07	11.378	1.661	13.039	8.34	2.063	0.32		0.655	1.661		
2007/08	10.629	1.39	12.019	8.46	1.338	0.281		0.55	1.39		
2008/09	24.465	1.085	25.55	16.25	6.43	0.525		1.26	1.085		
2009/10	8.079	0.887	8.966	6.104	1.31	0.47		0.195	0.887		0.332
2010/11	12.046	0.747	12.793	9.465	2.23	0.18		0.171	0.521		0.226
2011/12	11.622	1.306	12.928	7.096	3.921	0.336		0.27	1.065		0.242
2012/13	13.45	1.06	14.51	11.78	1.32	0.2		0.14	0.63	0.3	0.1

Description of the Richerenches and Carpentras basins

To study the relationship with climatic factors, only data from the market of Richerenches and Carpentras were analysed; these two locations represent respectively 57 and 20 % of the total volume traded in the markets. Richerenches is the most prominent market in France and in the world; it drains the truffle production of the alluvial basin of the Lez River, from South Drôme and North Vaucluse (North of Mont Ventoux). This basin forms an alluvial plain measuring approximately 520 km^2, in which the districts of Grignan, Saint-Paul-Trois-Châteaux and Valréas represent 85 % of the truffle orchards of this basin. In this flat area surrounded by limestone hills with superficial soils, the truffle orchards are mainly installed on deep brown calcarisols, with 1 to 3 % of organic matter, with a sandy–silty texture, high alkaline water pH (average 8.5) and high limestone content. Most commonly, along the rivers, the alluvial water table is less than 2 m deep. The Carpentras market, situated 40 km from Richerenches, drains the truffle production of another alluvial basin, that of the Ouvèze river, which flows into the Rhône, South of Mont Ventoux. The Carpentras basin is smaller than the Richerenches basin, with a more broken topography. The soils are also generally deep brown calcarisols but without an alluvial water table near the surface. These two markets drain the production of approximately 6,000 ha of nearby truffle orchards and occasionally from more distant areas with their own wholesale markets.

Climatic records

The meteorological data obtained from several weather stations of Météo-France consisted of monthly precipitation values (P in mm), average monthly temperatures (T in Celsius degree), average monthly evapotranspiration rates (Penman PET in mm calculated by the FAO Penman–Monteith method, 1990), the monthly number of days of frost fom January to March (year n) with a minimum temperature equal or below 0 °C (DF0) and the monthly number of days from January to March (year n) with a minimum temperature equal or below

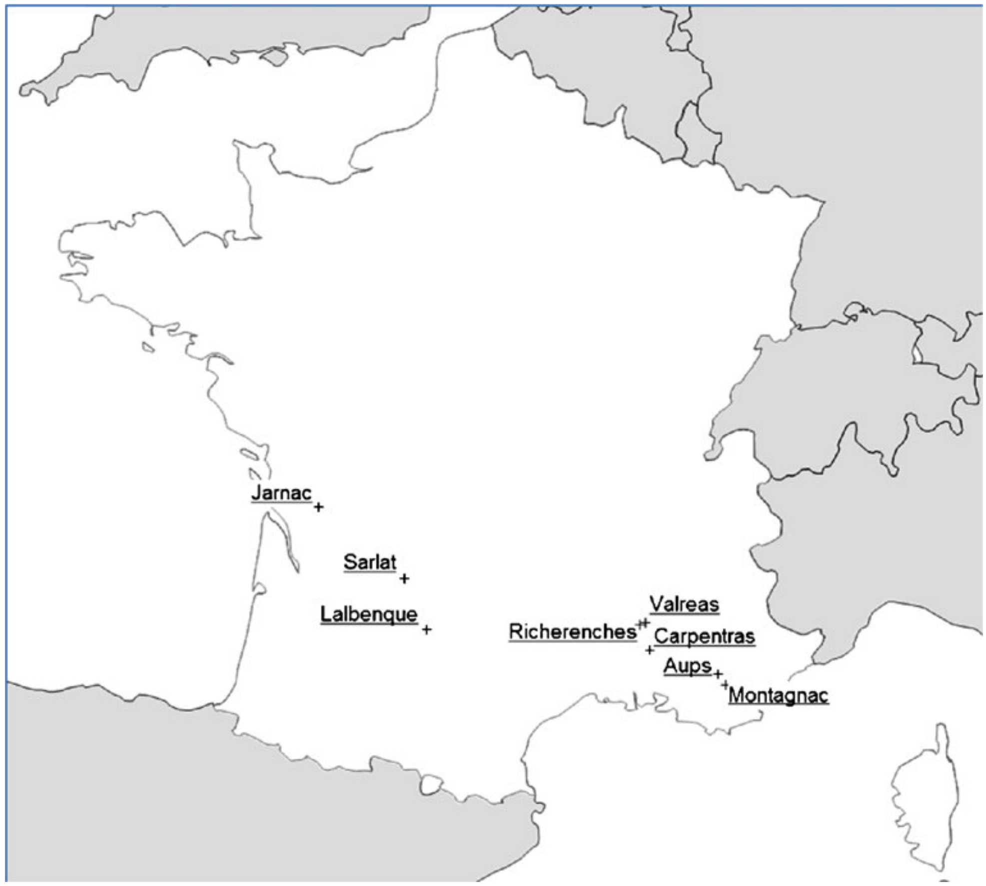

Fig. 1 Localization of the eight Périgord black truffle markets of southwestern and southeastern of France. Jarnac latitude 45° 68 north, longitude 0° 17 west; Sarlat latitude: 44° 89 north, longitude 1° 22 east; Lalbenque latitude 44° 34 north, longitude 1° 54 west; Richerenches latitude: 44° 35 north, longitude 4° 91 east; Valreas latitude 44° 38 north, longitude 4° 98 east; Carpentras latitude 44° 05 north, longitude 5° 04 east; Aups latitude 43° 62 north, longitude 6° 22 east; Montagnac-Montpezat latitude 43° 78 north, longitude 6° 09 east (decimal degrees from API Google Maps)

−5 °C (DF5). The monthly hydric balance (HB) was calculated as the difference between the monthly precipitations and the average monthly evapotranspiration (HB = P–PET in mm). P, PET and P–PET were calculated monthly or cumulated for several months.

P, T, DF0 and DF5 were obtained from Carpentras (station no. 84031001; latitude, 44°04′54″ N; longitude 5°03′30″ E, altitude 99 m) and Valréas near Richerenches (station no. 84138001, latitude, 44°22′48″ N; longitude 4°57′48″ E, altitude 122 m), while PET was obtained only from Carpentras. For the Richerenches basin, we used the Valréas data for most of the parameters except for PET that came from Carpentras. The use of the Carpentras PET for Richerenches is justified by the excellent correlations between the SAFRAN PET of the two sites (data not shown). The SAFRAN data from Météo France covers France with a resolution of 8 km on an enlarged Lambert-II projection (Le Moigne 2002) but was not available before 2007.

The period of truffle production starts in October–November and concludes in March of the following calendar year. The annual year of truffle production (year n) was thus considered from the first of April to the 31st of March of the following calendar year. The year $n-1$, whose climatic characteristics could affect the truffle production of the year n, was considered from the first of April of the previous calendar year to the 31st of March of the following calendar year.

To determine whether the climate significantly changed in the southeastern region of France, we analysed the meteorological data from the Carpentras station no. 84031001 and the Valréas station no. 84138001 over the period 1965–2012.

Statistical analysis

All statistical tests were considered significant at $P<0.05$ except for introduction of variables in forward regressions ($P<0.1$). The analysis of the 1988–1989 to 2012–2013 time series was based on multiple forward regression (Hocking 1976; Draper and Smith 1981; Weisberg 2005), which has been widely used for this type of study (Becker 1989; Becker et al. 1994; Lebourgeois et al. 2004, 2005). Climatic variable tested in the analysis were those we hypothesized to influence truffle production. They were based on the truffle cycle, i.e. temperature and moisture conditions at the time of truffle initiation (previous winter and spring), growth (summer, in particular water availability, and autumn) and harvest (in particular frost). At each step, the climatic variable having the greatest partial correlation coefficient among the remaining variables was introduced in the model. The regression was

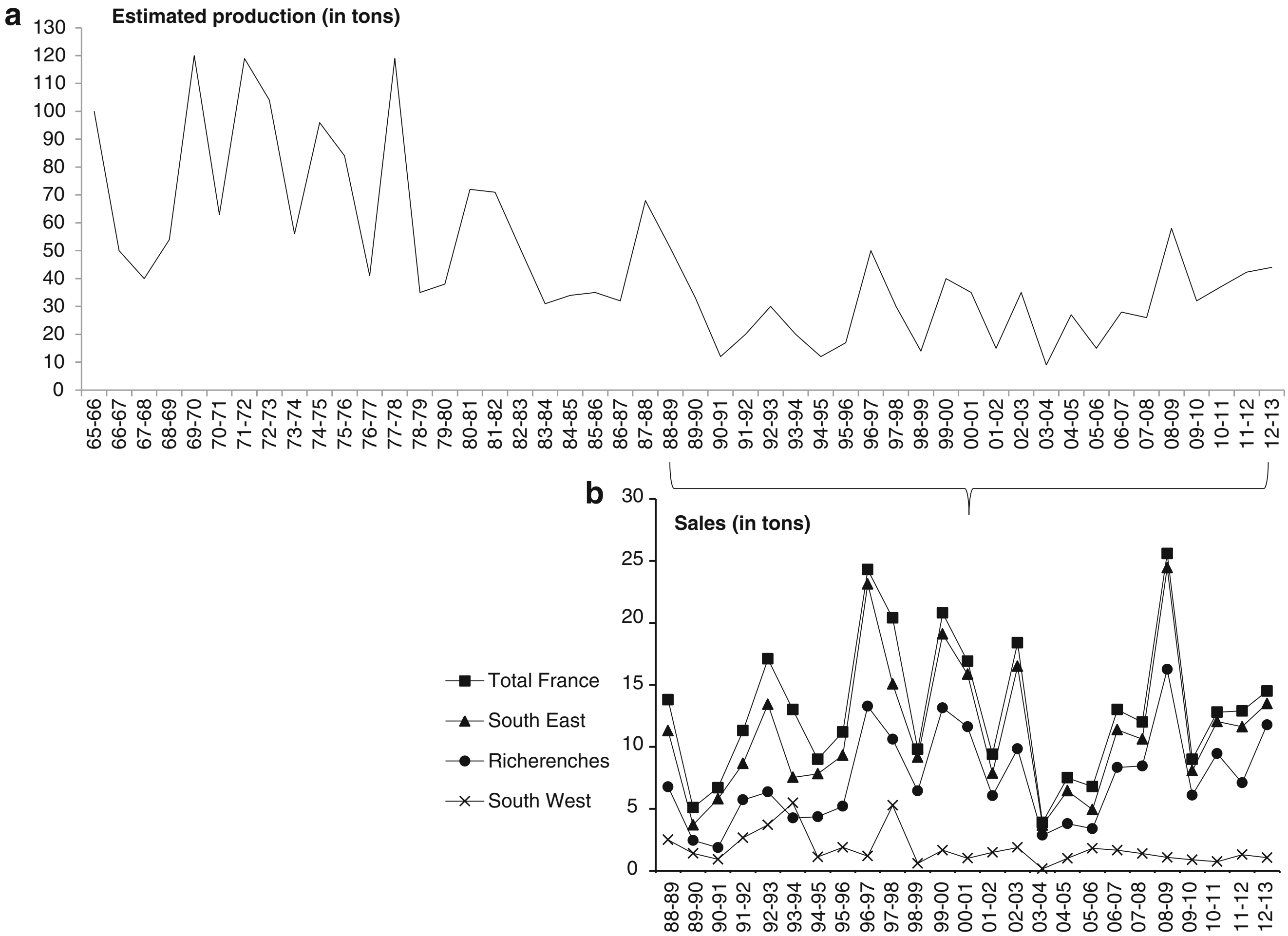

Fig. 2 Estimations of French black truffle production. **a** From 1965–1966 to 2011–2012 (in tons per year, source Fédération Française des Trufficulteurs). **b** Truffle sales in wholesale markets in all of France (*square*), southeastern France (*triangle*), Richerenches (*circle*) and southwestern France (*cross*) from 1988–1989 to 2012–2013 (in tons per year; source: Réseau des Nouvelles des Marchés" of the French Ministry of Agriculture)

stopped when the introduction of a new variable gave a nonsignificant partial F.

A long-term trend of sales during these 25 years could be affected by changes in orchard management such as watering or by the increase of existing truffle orchards or by additional changes. To prevent undesirable effects of such trends on regression involving meteorological data, we first fitted a linear regression of sales from each location over time. Although the regressions were not significant (Table 2), we nevertheless started the multiple forward regression on the detrended values (residuals centered on zero). The use of these residuals allowed us to more generally address the question of the autocorrelation between the year *n* and the year *n*−1. In Richerenches, the Pearson correlation coefficient of sales between the year *n* and the year *n*−1 was 0.253 (p nonsignificant). After linear adjustment and use of the residuals, it became 0.164 (nonsignificant).

In Carpentras, the Pearson correlation coefficient of the sales between the year *n* and the year *n*−1 was 0.186 (nonsignificant) before or after using the centered residuals. We then used the model obtained from 1988–1989 to 2012–2013 to simulate the evolution of the sales from 1965–1966 to

Table 2 Statistics of the linear regression applied to the sales in Carpentras and Richerenches over time from 1987–1988 to 2012–2013

	Carpentras	Richerenches
Intercept (s.e.)	3.563 (0.09)	−380.83 (198.18)
Slope (s.e.)	−0.0004 (0.049)	0.194 (0.09)
RMSE	1.784	3.573
R^2	3.75E-06	0.143
F (1,23 d.f.)	8.62E-05	3.838
p-values	0.9927	0.062

present day by considering the meteorological data available for the Richerenches and Carpentras basins.

Results

Truffle market sales and climatic variations in the southeastern region of France

In both the Carpentras and Richerenches markets, the cumulative hydric balance from May to August (HB = P-PET) of the year n was the most important factor, explaining 36.9 and 45.7 % of the variation in truffle sales, respectively (Table 3 and Fig. 3). The more negative cumulative hydric balances from May to August were associated with the lowest truffle sales.

In Carpentras (Table 3), the cumulative rainfall in November and December of the year n explained an additional 20.4 % of the variation (positive effect). The other factors had less importance: the cumulative PET of February and March of the year n explained 12.1 % of the variation (positive effect); rainfall in January during the year $n-1$ explained 5.1 % of the variation (positive effect); and the cumulative rainfall of November and December of the year $n-1$ explained 6.5 % of the variation (negative effect). There were no great divergences between the model (multiple linear regression at five variables) and the actual sales (Fig. 4).

In Richerenches (Table 3), in contrast to Carpentras, the second factor with an influence on truffle sales (negative effect) was the number of freezing days with a minimum temperature equal to or less than −5 °C (DF5 of the year n); it explained 14 % of the variation in truffle sales. The cumulated PET of February of the year n explained 7.8 % of the variation; the January rainfall of the $n-1$ year (positive effect) explained 5.4 % of the variation. For the years 1999–2000 and 2000–2001, there were more sales than predicted by the model (multiple linear regression at five variables). Inversely, in 1993–1994, 1994–1995, 2003–2004 and 2004–2005, the sales were lower than predicted (Fig. 4).

Climate evolution in the Carpentras and Richerenches basins from 1964 to 2012

For the last 48 years (1964 to 2012), climatic conditions have evolved in the study area (Fig. 5). In both the Carpentras and Richerenches basins, the average annual precipitations were stable (the increase was not significant), whereas summer rainfall significantly decreased. The mean annual and summer temperatures increased respectively by 0.8 and 1.4 °C. The annual and summer evapotranspiration rates also significantly increased. Consequently, the hydric balance (HB = P−PET) significantly decreased from May to August during the summer in Carpentras (Fig. 5a) but not significantly in Richerenches (Fig. 5b).

The number of days when frost occurred below −5 °C from January to March (year n) decreased sharply in the Richerenches basin. From 1964 to 1987 (24 years), there were 5.09 days of frost below −5 °C per year from January to March (year n), while only 2.36 days were observed during the same months from 1988 to 2012 (25 years). In contrast, for the Carpentras basin, there was no difference between the two periods.

Simulation of truffle sales in Carpentras and Richerenches from 1965–1966 to 2012–2013

In Carpentras and Richerenches, the climatic model established from 1988 to 2013, applied to the period 1965–1966 to 1987–1988, showed complete stability (p-value = 0.966 and 0.596, respectively) (Fig. 4). In both basins, the annual variations due to the weather conditions appeared equally important over the period 1965–1966 to 1987–1988 as for the period 1988–1989 to 2012–2013.

Estimation of the evolution of total French black truffle production from 1965 to 2013

The estimations of truffle production provided by the "Fédération Française des Trufficulteurs" for the period 1965–1966 to 1987–1988 are less reliable than the estimations based on the data of the wholesale markets for the period 1965–1966 to 2012–2013. According to these estimations already published (Callot et al. 1999; Olivier et al. 2012; Büntgen et al. 2012a), annual variations are observed with a continue decrease until 1991 (Fig. 2a). From 1991 to the present day, the production appears to be stable with annual variations and an increasing tendency observed during the last 5 years (Fig. 2a).

Discussion

French truffle production has been stable for the last 25 years

According to Olivier et al. (2012), at the end of the nineteenth century, 75 % of French truffle production occurred in southeastern France. Today, almost 90 % of French truffle sales occur in that same region. Over the last 25 years, this trend has persisted, with sales in southwestern France decreasing at a statistically significant rate. However, despite this decrease in sales in the southwestern region of France over the past 25 years, sales proved stable for the whole of France (with an average of 12.9 tons per year). The estimation of the French production provided by the "Fédération Française des Trufficulteurs" shows equal stability for the same period, contrary to the assertions of Büntgen et al. (2012a). Büntgen

Table 3 Multiple forward regression between meteorological variables and sales from 1988 to 2013 in the Carpentras and Richerenches black truffle wholesale markets

Carpentras							Richerenches						
	Mean (s.e.)	Estimate	R^2	Partial R^2	Partial F	Pr (>F)		Mean (s.e.)	Estimate	R^2	Partial R^2	Partial F	Pr (>F)
Sales in tons	2.65 (1.75)						Sales in tons	7.42 (3.5)					
Sales in tons (centered residues)	0 (1.75)						Sales in tons (centered residues)	0 (3.5)					
Model													
RMSE	0.854						RMSE	1.984					
R^2	0.811						R^2	0.732					
F (5,19 d.f.)	16.26						F (4,20 d.f.)	13.63					
p-value	2.73E-06						p-value	1.61E-05					
Parameters													
Intercept		−1.5485					Intercept		−0.349				
Cumulated hydric balance from May to August (HB = P-PET), year n in mm	−502 (93.4)	0.0086	0.369	0.369	18.75	0.0004	Cumulated hydric balance from May to August (HB = P-PET), year n in mm	−439 (137.5)	0.012	0.457	0.457	12.85	0.002
Cumulated rain from November to December, year n in mm	116.8 (76)	0.0085	0.573	0.204	12.84	0.002	Number of days with a temperature equal or below −5 °C (DF5), year n (months 1 to 3)	2.36 (2.51)	−0.370	0.599	0.142	8.73	0.008
Cumulated PET from February to March, year n in mm	42.10 (30.5)	0.046	0.694	0.121	5.7	0.0276	Cumulated PET of February, year n in mmm	32.15 (4.98)	0.188	0.678	0.078	5.23	0.033
Rain of January, year n−1 in mm	114.7 (75.7)	0.0195	0.746	0.051	8.79	0.008	Rain of January, year n−1 n mm	59.57 (51.35)	0.018	0.732	0.054	4.02	0.059
Cumulated rain from November to December, year n−1 in mm	103.7 (9.9)	−0.0065	0.811	0.065	6.5	0.0196							

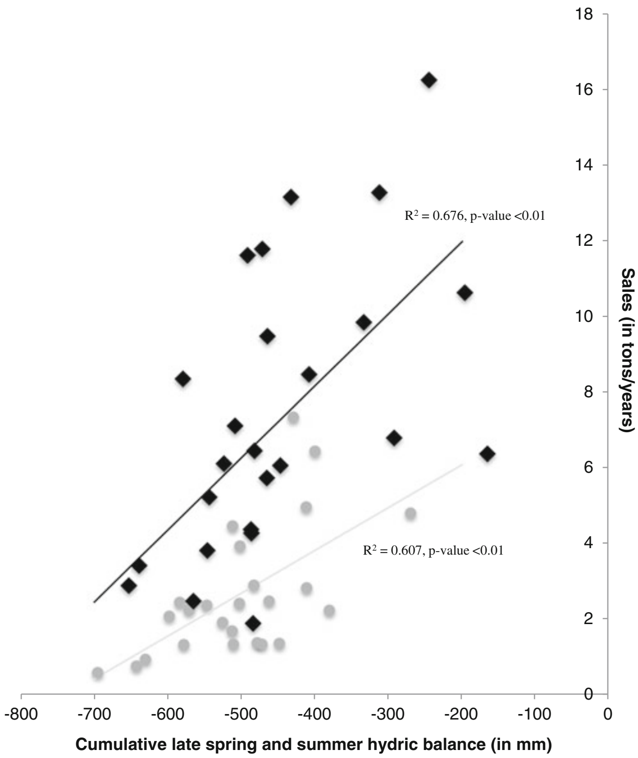

Fig. 3 The relationship between sales (in tons per year) from 1988–1989 to 2012–2013 and the cumulative hydric balance of year n (P-PET from May to August, in mm) in Carpentras (*grey cricle*) and Richerenches (*black square*)

et al. (2012a) used for France the estimation provided by the "Fédération Française des Trufficultueurs", but they did not include in their analysis data taken from 2007 to 2012. Interestingly, we observed a tendency towards increase over the last 5 years in French production (Fig. 2a).

The annual black truffle sales variation largely explained by weather

The stability of black truffle sales over the last 25 years is not indicative of important annual variations ranging from 4 to 25 tons per year. The analysis of the Richerenches and Carpentras wholesale markets revealed that the most important factor explaining these variations was the effect of the cumulative hydric balance from May to August (HB = P−PET) of the year n, which explained 36.9 % of the sale variation in Carpentras and 45.7 % of the sale variation in Richerenches. We therefore confirmed the importance of the negative effect of the spring and summer hydric deficit on truffle production as previously reported (Le Tacon et al. 1982; Büntgen et al 2012a, b). The second factor explaining the sale variations in the Richerenches basin was the number of days with minimum temperature equal to or below −5 °C (DF5) during the year n. This factor is well known to truffle professionals; however, to our knowledge, its involvement has never been previously statistically demonstrated. We did not find an effect of this factor in Carpentras, where the number of freezing days did not decrease over the last 25 years, while it decreased in Richerenches.

For both sites, other factors such as cumulative rainfall from October and November (year n) could affect sale variations but are of less importance than the cumulative hydric balance from May to August of the year n. Rainfall in October and November allow the growth of young truffles, which have survived the summer. Consistent water availability in late winter could also support the formation of new mycorrhizas, thus allowing a new cycle. The occurrence and initiation of sexual reproduction is largely unknown (Murat et al. 2013). Healy et al. (2012) identified mitospores in Pezizomycetes and in *Tuber* spp. that appeared to be induced by rainfall. If mitospores are important for *Tuber* sexual reproduction, as suggested by Healy et al. (2012), we can make the assumption that rainfall is critical not only for ascocarp and mycorrhizal growth during the year n but also for initiation of sexual reproduction throughout development of the mitospores, which is expected to occur in late winter or spring of the year $n-1$. Indeed our finding of a significant positive correlation between January precipitations of the year $n-1$ and truffle sales in both Richerenches and Carpentras support this hypothesis.

Overall, the Richerenches results appear to be of greater biological relevance than those of Carpentras. This might be explained by the large quantity of truffles sold in Richerenches, allowing more opportunity to highlight the role of the most relevant meteorological variables.

Nevertheless, for 2 years in Richerences, there were more observed sales than predicted by the model. For these years, contributions from areas outside of the basin might have been included in the sale data. Inversely, for three years, sales were lower than those predicted by the model. In these cases, direct sales to traders before the market openings were likely not included in the data provided by the French Ministry of Agriculture. We examined the weekly evolution of the truffle markets during these particular time periods but were not able to explain these distortions.

Despite these biases, data obtained in Richerenches were sufficiently reliable to allow us to identify the two main factors explaining annual variations in truffle production: the cumulative hydric balance from May to August of the year n and the number of extremely cold days from January to March of the year n.

Climate change does not explain the decrease in black truffle production over the last 48 years

Our results showed that in the past 48 years, the hydric balance has decreased during the summer months in both the Carpentras and Richerenches basins, while the

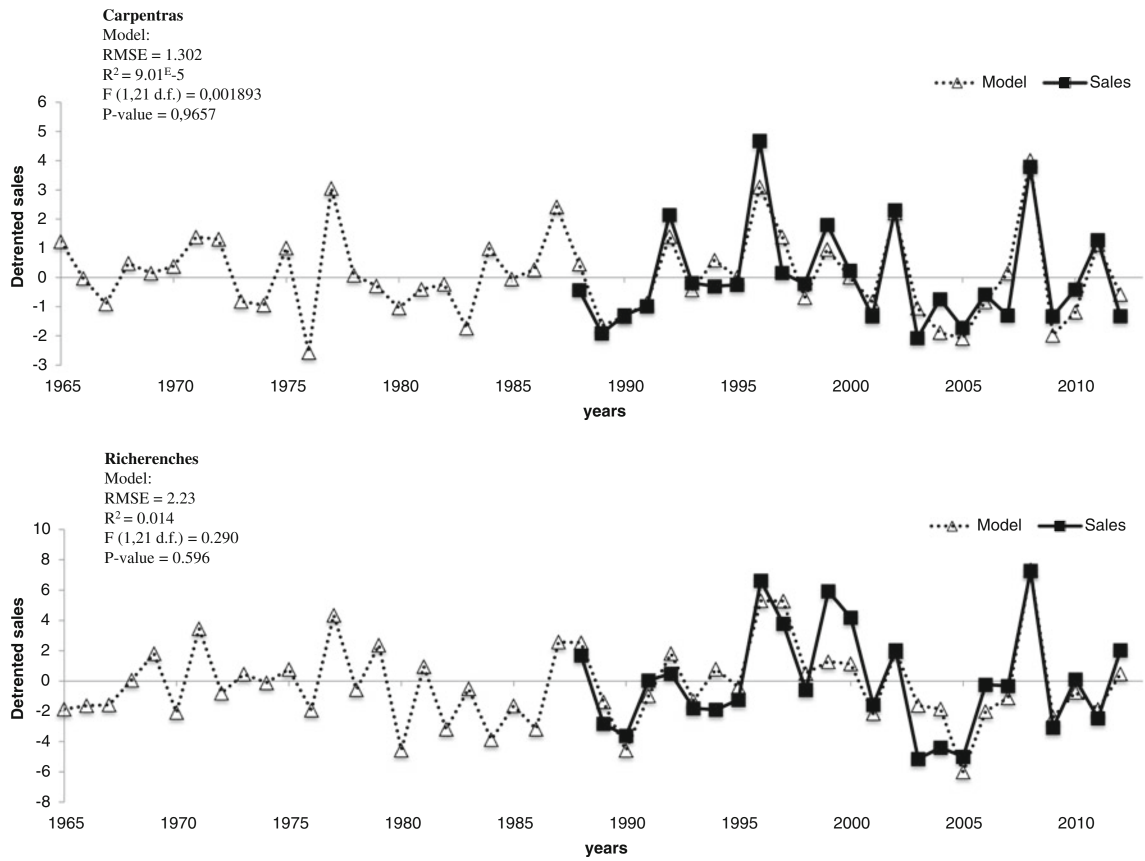

Fig. 4 Evolution of the detrended truffle sales in wholesale markets from 1988–1989 to 2012–2013 (*square continuous line*) and of the multiple linear regression model from 1965–1966 to 2012–2013 (*triangle dotted line*) in Carpentras and Richerenches. The statistics of the multiple linear regression of the predicted sales over time for the period 1965–1966 to 1987–1988 are indicated, showing a stability

number of frost days equal or below −5 °C decreased in Richerenches. The multiple regression models based on climatic parameters explain at least 73 % of the sale variability during the period 1987–1988 to 2012–2013. The same models applied to the period 1964–1965 to 1986–1987 show temporal stability.

During the same period, French global truffle production greatly decreased (Fig. 2a). The contradiction between this decrease and the stability of our sale model based on climatic variables suggests that climate evolution cannot explain the fall observed for all production in France. We can also make the assumption that degradation of the summer hydric balance was compensated by the reduction of the number of days at freezing temperatures, at least in Richerenches. Nevertheless, the extrapolation of the 1988–2013 model for the 1964–1987 period should be interpreted with caution, particularly because our model could underestimate drought impact due to actual watering. However, climate change does not seem to be the main factor explaining a decline in French truffle production from 1965 to 2013. French society as well as the French agricultural community experienced significant changes following the Second World War with rural desertification (Olivier et al. 2012). Traditional agriculture for subsistence was replaced by intensive agriculture in which truffle production, which is known to be unpredictable, did not correspond with the new technical-economic model. During the same period, traditional practices (e.g. use of wood for heating and cooking, harvest of litter for cowshed, pastoralism) were abandoned, which lead to changes in the ecosystems where truffles were traditionally harvested. Rural depopulation and landscape changes in the Mediterranean region are well documented (Barbero et al. 1990; Ales et al. 1992; Chauchard et al. 2007). A sampling of the vegetation in 193 plots in the Montpellier region (France) between 1978 and 1992 showed that the cover of woody plants increased significantly (Preiss et al. 1997). Among the consequences of this mutation were a pronounced decrease of land surface naturally devoted to truffles and abandoned management of the old truffle orchards (Olivier et al. 2012). Our results suggest that the decline in French truffle production over the last 48 years could be attributed more to the changes in rural communities than to climatic changes.

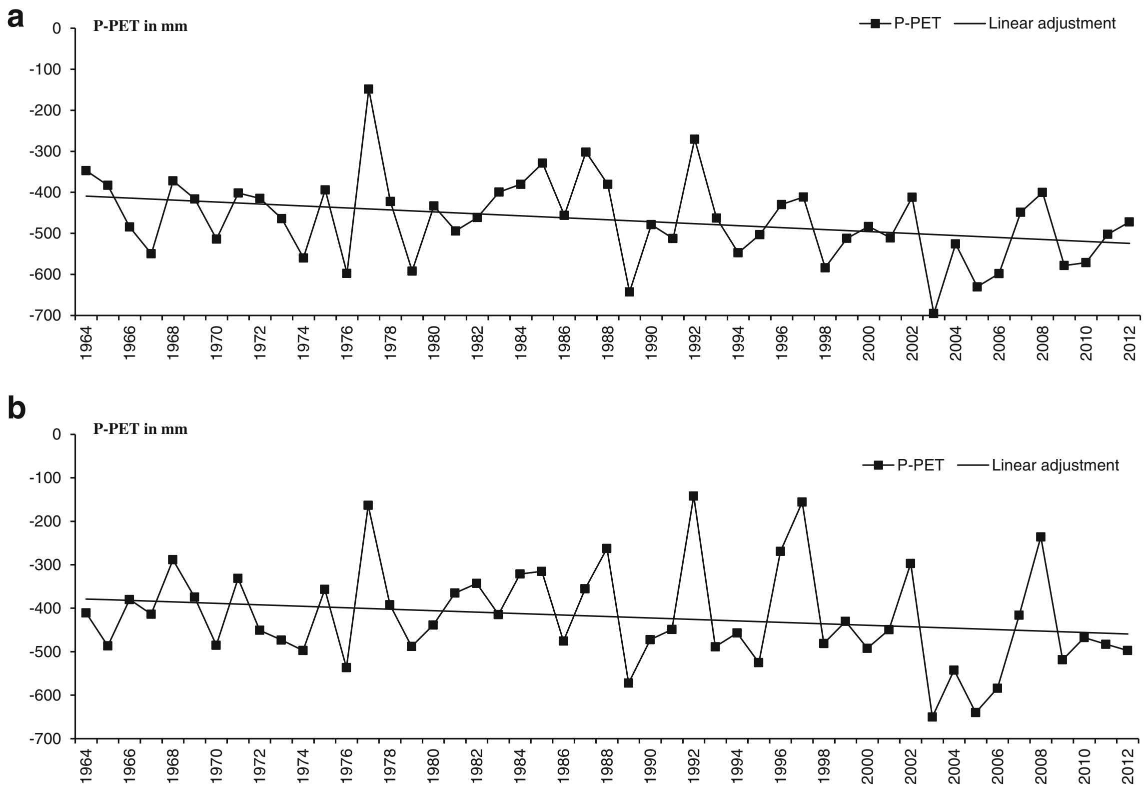

Fig. 5 Evolution of the cumulative hydric balance (P-PET) from May to August, in mm, in Carpentras (**a**, R^2=0.34; p<0.05) and in Richerenches (**b**, R^2=0.21; p<0.20) from 1964 to 2011

Conclusion

In the Richerenches wholesale market, which represents 57 % of the total volume traded in the French markets, we have identified from 1988 to 2013 the two main factors explaining annual variations in truffle production: the cumulative hydric balance from May to August of the year *n* and the number of extremely cold days in the winter of the year *n*. The simulation of potential truffle sales from 1965 to 2013 showed that, according to the climatic conditions, truffle sales would have been stable during these past 48 years despite a degradation of the summer hydric balance, which could be compensated by the reduction of the number of days equal or below −5 °C. Consequently, climate change does not seem to be the main factor explaining a decline in French truffle production from 1965 to 1987. The explanation for this period and the previous one (1900 to 1964) has probably to be found in the decrease of land surface devoted to truffles and abandoned management of the old truffle orchards.

Today, more than 80 % of truffle production occurs in truffle orchards that have been planted with seedlings previously inoculated with truffle spores in nurseries (Olivier et al. 2012). In these orchards, management techniques, such as watering, can alleviate summer water deficits.

However, if degradation of the summer hydric balance continues, it will become increasingly necessary to improve implementation of all techniques possible that would allow the improvement of the summer hydric balance such as eliminating herbaceous vegetation, soil tilling and decreasing tree evapotranspiration rates by diminishing host stem density and reducing tree crowns. A great deal of progress remains to be made to persuade truffle growers to implement these techniques and to establish clear standards and technical programs for truffle orchard management.

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