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Black truffle harvesting in Spanish forests: trends, current policies and practices, and implications on its sustainability

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Abstract

The European black truffle is a mycorrhizal fungus native to Spanish Mediterranean forests. In most Spanish regions it was originally commercially harvested in the second half of the 20th century. Experts agree that wild truffle yields suffered a sharp decline during the 1970s and 1980s. However, official statistics for Spanish harvest are scarce and seemingly conflicting, and little attention has been paid to the regime for the exploitation of truffle-producing forests and its implications on the sustainability of this resource. Trends in harvest from 1969 to 2013 and current harvesting practices were analyzed as a case study, taking into account that Spain is a major truffle producer worldwide, but at the same time truffles have only recently been exploited. The available statistical sources, which include an increasing proportion of cultivated truffles since the mid-1990s, were explored, with estimates from Truffle Harvesters Federation showing higher consistency. Statistical sources were then compared with proxies for wild harvest (rents from truffle leases in public forests) to corroborate time trends in wild harvesting. Results suggest that black truffle production is recovering in recent years thanks to plantations, whereas wild harvest is still declining. The implications of Spanish legal and institutional framework on sustainability of wild truffle use are reviewed. In the current scenario, the decline of wild harvest is likely to continue and eventually make commercial harvesting economically unattractive, thus aggravating sustainability issues. Strengthening of property rights, rationalization of harvesting pressure, forest planning and involvement of public stakeholders are proposed as corrective measures.

Keywords: Mediterranean forests, natural resource management, non-timber forest products, sustainable harvesting, *Tuber melanosporum*

1 Introduction

Non-timber forest products (NTFPs) have contributed to the welfare of rural populations in the Mediterranean region, where timber productivity is usually low (Blondel 2006). However, practitioners and policy makers have not always properly valued their contribution. Some NTFPs lack a market price or are sold in informal markets, while many are poorly known (Croitoru 2007). This situation has resulted in low interest from forest owners and has frequently led to abandonment of forest management and non-optimal use of resources (Palahi et al. 2008).

Edible mushrooms are one of the NTFPs traditionally harvested in Mediterranean forests (Boa 2004). The European black truffle (*Tuber melanosporum* Vittad.) is the most prized wild edible fungus in some Mediterranean countries, yielding a multi-million euro industry in Spain, France and Italy (Reyna and Garcia-Barreda 2014). In most Spanish regions it had not been harvested before the 1940s, but from that moment declining harvests in France encouraged commercial harvesting (Callot 1999; Reyna 2012a).

Harvesters and experts agree that Spanish wild truffle production suffered a sharp decline during the 1970s and the 1980s (Reyna 2012b). However, official statistics for truffle harvests are scarce and seemingly conflicting, making it difficult to quantify production and trends. Most experts agree that habitat deterioration, overexploitation and climate change are major causes of decline (Reyna 2012b). The influence of habitat and climate change on truffle production has been addressed in scientific studies (Büntgen et al. 2012; Garcia-Barreda and Reyna 2013), whereas little attention has focused on harvesting pressure and regulation despite the concerns expressed by Pilz and Molina (2002) and Boa (2004) about the long-term impact of these factors on other wild edible mushrooms.

Here we used the black truffle harvest in Spain as a case study of socio-political issues challenging sustainable exploitation of wild fungi, taking into account that this country is a

major truffle producer worldwide, but at the same time truffles have only recently been exploited there. Specifically, we aim: (i) to explore the analysis of official statistics to characterize trends in wild black truffle harvest in the period 1969-2013, and (ii) to discuss implications of current harvesting policies and practices on the sustainability of wild truffle harvesting.

2 Methods

2.1 Study site: Spanish legal and institutional framework

Before the 20th century there are few historical records of truffle harvesting in Spain, restricted to Barcelona province (Morcillo et al. 2007). In the 1940s harvesting began to spread within the Pre-Pyrenees and later southwards, reaching eastern Spain provinces such as Teruel and Castelló in the late 1950s (Reyna 2012a). Truffle harvesting always had a commercial aim. The great majority of harvest is exported to France even nowadays, with Spanish harvesters frequently selling truffles in informal markets and truffles entering formal markets through traders (Oliach et al. 2009).

According to the Spanish Civil Code truffles belong to the landowner by accession. Landowners can harvest truffles in their properties, explicitly or tacitly allow harvesting by others, forbid harvesting, or retain the harvesting rights and lease these rights to another harvester (Gil-Martínez et al. 2001). In private forests, all these situations have been common, as well as landowners being unaware that their forests produced truffles.

However until the 1970s truffles were frequently harvested without the agreement of the landowner. In 1972 the national government regulated the harvesting practice and approved a sanctioning framework for poaching (Supplementary Material: Table S1). Then the government and municipalities reserved the harvesting rights of public forests with relevant truffle production. Since then exclusive harvesting rights of these forests are granted at

sealed-bid auctions with a floor price. If no bid reaches the floor price the auction is repeated and if it happens again the truffle harvest remains non-leased for a year. The highest bidder signs a lease contract and the corresponding technical specifications, ordinarily requiring only compliance with harvesting regulations (Supplementary Material: Table S1). In public forests truffle leases usually have a total term of two to six years, with no limitation on the amount of truffles to harvest. The lessee pays the bid as an annual rent. The contract finishes when the lease term is ended or if the lessee does not pay the annual rent. In private forests, lease contracts have customarily been verbal and just specifying the annual rent (Gil-Martínez et al. 2001).

During the 1980s Spain developed a highly decentralized government system and jurisdiction over truffle harvesting was transferred to regional governments. Most of them gave continuity to the 1972 national regulation (Supplementary Material: Table S1). Additional efforts to promote a more professional attitude among harvesters have been scarce, with Catalonia leading efforts to regulate harvesting and fight poaching (Supplementary Material: Table S1) and Valencian Community encouraging habitat rehabilitation with subsidies and a demonstrative pilot project (Garcia-Barreda and Reyna 2013). Property rights of landowners were reinforced by Spanish state forest law 43/2003 –and the corresponding regional laws– establishing that forest products such as truffles belong to the landowner. However, no national or regional strategy for sustainable use of wild edible fungi is currently underway.

2.2 Statistical sources for truffle harvests

First explicit official statistics in Spain appeared in 1969, when truffles were explicitly incorporated in the International Trade Statistics Yearbook (ITSY) from the Spanish Ministry of Finance (Dirección General de Aduanas 1969-2015). ITSY details weight exported on a yearly basis, with customs forms being the data source (Table 1). It includes fresh truffles

(including those refrigerated) and preserved truffles (including those frozen). From 1995 onwards data are disaggregated by month.

Agricultural Statistics Yearbook (ASY), the official statistical source from Ministry of Agriculture, incorporates a section about truffles from 1973 (transferred to Forest Statistics Yearbook in 2005) that includes estimations of weight harvested in the wild (Ministerio de Agricultura 1973-2004, Banco de Datos de la Naturaleza 2005-2013). The methodology for estimating harvests is not detailed, with recent yearbooks acknowledging low reliability and heterogeneous criteria among regions and from year to year. Estimates before 1998 were not disaggregated by land ownership. Meanwhile in recent years some regions submit estimations for harvests in private and public forests while others simply submit prospective estimates for public forests obtained from regional operating plans (Table 1).

Spanish Federation of Associations of Truffle Growers (FETT) provides its own estimate for black truffle harvest in Spain, going back to 1970 (Table 1). Although estimates for the 1970s and the 1980s are retrospective and their quality has not been assessed before, they have been implicitly recognized as reliable datasets by scientists using them for climate change studies (Büntgen et al. 2012).

Finally, we collected data of annual rents from lease agreements for black truffle harvesting in forests under public administration in Teruel and Castelló provinces (PTL), two of the foremost harvesting areas, to obtain an independent and homogeneous dataset for assessing time trends in wild harvest. However these data are neither systematically stored nor retrievable from ASY, so we could retrieve data for only a limited number of years from the archives of regional governments, the Ministry of Agriculture and from Soriano (2000) (Table 1).

2.3 Data analysis

Statistical sources for national truffle production were explored to clarify the meaning of variables and the consistency of time series. Agreement among sources was analyzed and methodologies of data collection were assessed. Agreement among sources was studied through Pearson correlation coefficients. Among all possibilities for ITSY data, we selected the weight of pooled fresh and preserved truffles exported worldwide from Spanish traders (Table 1). Other possibilities were also explored, but results did not provide further insight and are not shown.

Two additional approaches were used to assess the consistency of time series. The first one is based on truffle biology. Black truffles grow in obligate symbiosis with oak roots and sporocarps depend on carbon supply from the host tree almost until full ripeness (Le Tacon et al. 2013). Thus a correlation between fungal fruiting and tree growth is expected. We quantified growth of holm oak (*Quercus ilex* L), the main host species for black truffle in Spain, by using dendrochronology and obtaining standardized mean chronologies (mean series of indexed tree-ring width) in two locations from the main truffle-producing areas (Iberian System and Pre-Pyrenees; Camarero et al. 2016). We used annual radial growth, quantified as standard ring-width indices (i.e. with first-order autocorrelation) as a proxy for potential of truffle production (Büntgen et al. 2012).

The second approach is based on knowledge of major distribution channels of Spanish truffle and monthly disaggregation in ITSY data from 1995 onwards. We used fresh truffles exported worldwide from December to February ($ITSY_{dec\text{-}feb}$) as a proxy for black truffle harvest (Table 1). This approach takes advantage of the facts that: (i) Spanish black truffle is mostly exported fresh during harvesting season, (ii) black truffle season occurs in a time frame completely different from *Tuber aestivum* Vittad., the other native species that Spain exports in large quantities, and (iii) black truffle price drastically differs from *T. aestivum* and Asiatic truffles

such as *Tuber indicum* Cooke & Massee, thus allowing an easy identification of months in which significant quantities of these species were exported. The harvesting season of black truffle also includes November and March, but these months were not incorporated because half of the recorded years showed either prices or weights clearly indicating an error or a significant presence of other truffle species. A correlation between $ITSY_{dec\text{-}feb}$ and the remaining data sets is expected. In addition, it is expected that $ITSY_{dec\text{-}feb}$ data account only for a fraction of the total harvest. The latter was studied through the coefficients of simple linear regression models.

Finally, the soundness of PTL data sets as proxies for wild black truffle harvest was explored. Agreement of PTL data sets with raw harvest data and with harvest data smoothed by cubic splines were examined. In the latter ring-width indices were used as predictors to disentangle interannual harvest fluctuations linked to weather conditions (Ricard et al. 2003) and adjust for the fact that rents are likely much less sensitive to these fluctuations.

3 Results and discussion

3.1 Spanish truffle production

No significant correlation between ITSY data and other sources were found (Table 2). The positive time trend in ITSY data, together with several years showing extremely high values such as 1994, 1999, 2003, 2007 and 2011 (Fig. 1), indicate that other truffle species such as *T. aestivum* and *T. indicum* show a quantitatively relevant presence in ITSY statistics. The weight of Asiatic truffles is supported by the fact that according to ITSY Spanish import of truffles was only relevant from 1986 onwards, around the time that Asiatic truffles first arrived to European markets (Wang and Liu 2010).

Another discrepancy that is potentially affecting correlation between ITSY and other sources is the differing time basis of data sets, with the former using calendar years and other sources

referring to black truffle harvesting seasons. IASY apparently uses calendar years, but comparison with PTL reveals that in recent years PTL corresponds with ASY estimates for public forests in Castelló province, thus suggesting that in practice black truffle harvesting season is the time basis for this source (i. e. ASY sorts truffles harvested in leased forests in the year in which the rent was paid, despite the fact that some of these truffles are harvested in January-March of the following calendar year). Correlation of ITSY data with one-year lagged ASY and FETT estimates did not yield any significant Pearson correlation either (data not shown).

Although ASY and FETT showed somewhat more similar trends (Fig. 1), their correlation is not significant (Table 2). Black truffle harvests dramatically fluctuate from year to year due to the close relationship of truffle fruiting and weather (Ricard et al. 2003). However ASY data is contributed to a large extent by rents from truffle leases in public forests, which are multiannual. These rents depend on harvest amounts in previous years and harvesters forecast for the following seasons, thus making ASY estimates less responsive to actual year-to-year weather fluctuations (Fig. 1).

Another discrepancy that is potentially affecting correlations between ASY and other sources is the fact that ITSY and FETT include production from truffle plantations, whereas ASY does not. In recent decades wild harvest decline and high prices encouraged truffle cultivation. Most plantations are established in agricultural lands, which are located outside the forest properties where truffles naturally fruit (Reyna and Garcia-Barreda 2014). Truffle plantations constitute a significant proportion of the national production since the large Arotz plantation – situated in northern Spain– began to produce, with season 1998-1999 being the first in which it accounted for at least 10% Spanish harvest according to the company (Büntgen et al. 2015). However excluding data from 1998 onwards did not improve the significance of correlations between ASY and other sources (data not shown).

The lack of agreement among data sources raises doubts concerning their reliability. Thus these sources were correlated with other potential proxies for truffle harvest: tree growth and $ITSY_{dec\text{-}feb}$.

Ring-width indices (tree growth) showed a significant correlation with FETT, but not with other sources (Table 3). Excluding data from 1998 onwards improved the correlation coefficient with FETT ($r = 0.77$, $P < 0.001$), suggesting that increase in plantations production could alter this relationship.

For the period 1995-2015, $ITSY_{dec\text{-}feb}$ showed a significant correlation with FETT and ASY, but not with ITSY (Table 3). Since both $ITSY_{dec\text{-}feb}$ and FETT stand for pooled production of wild and cultivated black truffle, with $ITSY_{dec\text{-}feb}$ including only a fraction of the harvesting season, it might be expected that the regression coefficient between $ITSY_{dec\text{-}feb}$ and FETT would be higher than one. However the regression coefficient did not significantly differ from one at the 95% significance level (1.39, with confidence interval: 0.80 to 1.99), while the intercept term did not significantly differ from zero (3500 kg, with 95% confidence interval: -8200 to 15200).

FETT is the only source correlating with both tree growth and $ITSY_{dec\text{-}feb}$, indicating that it is the source with higher consistency and usefulness for evaluating trends in Spanish production of black truffle. ITSY includes other truffle species that hamper its use as a proxy for black truffle production. However, monthly disaggregation from 1995 provides an opportunity for using this source as proxy, since Spanish internal consumption of black truffle is considered to be very low (Oliach et al. 2009). ASY estimates from 1995 may have some potential value as proxy for black truffle production, as suggested by agreement with $ITSY_{dec\text{-}feb}$. However the heterogeneity and lack of detail about the criteria by which ASY is estimated make it difficult to assess the reliability of ASY data, thus discouraging its use despite the fact that it would be the only source specifically estimating wild harvest.

3.2 Wild harvest

PTL from Castelló showed a significant correlation with raw FETT estimates (Table 2) and smoothed FETT estimates ($r = 0.94$, $P = 0.001$), but not with ITSY (Table 2). The magnitude and pattern of decline in truffle rents from Castelló is similar to FETT estimates for national harvest (Fig. 2), thus supporting usefulness of PTL for assessing trends in wild harvest despite the fact that they actually account for rents from truffle leases.

On the other hand, no significant correlation between PTL in Teruel and the aforementioned sources were found (Table 2; $r = 0.27$, $P = 0.56$ for smoothed FETT). Our data suggest that decline in Teruel wild truffle harvest began later than in other regions (Fig. 2). According to harvesters from Teruel, decline began in the mid 1980s (Estrada and Perales 2013), with our data showing that PTL did not respond to this decrease at least until 1992. This indicates the existence of regional specificities in the timing of decline.

ASY harvest estimates showed a significant correlation with PTL from both Teruel and Castelló provinces (Table 2). Rents from truffle leases in public forests are a major source for ASY estimates and these are two of the foremost harvesting areas, so this was an expected result.

Smoothed FETT estimates suggest that Spanish production is slowly recovering since around season 2000-2001, while PTL continues to fall since the 1990s to the present day both in Teruel and Castelló provinces (Fig. 2). The discrepancy is likely due to truffles produced in plantations, which have risen from around 10% national production in 1998 (Büntgen et al. 2015) to around 60% in 2012 (Reyna and Garcia-Barreda 2014).

The continued decline in wild black truffle harvest highlights the scarce sustainability of past and current harvesting and management practices and the threat to conservation of this fungus in the wild. Declining black truffle harvest has been generally attributed to a combination of

factors including habitat deterioration, overharvesting and climate change (Reyna 2012b). Unlike habitat deterioration and climate change, little attention has focused on the long-term effect of intensive commercial harvesting. The regime for the exploitation of Spanish truffle-producing forests is outlined below, with a focus on its relation with harvesting pressure and sustainability.

3.3 Implications of policies and regulations on harvesting sustainability

Private forests harvested by the landowner with no poaching issues provide complete property rights over NTFPs and create optimal conditions for sustainable use and management. Departures from exclusive, enforceable, perpetual, comprehensive and transferable rights of use may reduce incentives for sustainable use and investment in NTFPs (Tedder et al. 2002; Ros-Tonen and Kusters 2011). In truffle-producing forests of Spain, various degrees of departure occur depending on the regime for the use of the resource: (i) forests where harvesting is *de facto* open access, (ii) forests plagued by poaching, (iii) forests –mostly public– harvested collectively with no cooperation among harvesters, and (iv) forests exploited by individual lessees (hereafter called "private harvesters").

Poaching and situations of *de facto* open access (by explicit consent, tacit consent or by owner's lack of awareness) create an environment with little incentive for sustainable harvesting and owner's investment in NTFPs (Tedder 2008). But, as pointed out by Gil-Martínez et al. (2001), Spanish forests exploited by private harvesters are also generally subject to abusive extraction and resource depletion –and these leases have been the general rule in public forests and quite common in private lands. Private harvesters have no incentive to avoid overharvesting, being that future availability of truffles will be decided on an auction based solely on the economic bid. Public and private landowners, in turn, traditionally attached little value to truffle harvesting and did not invest in specific forest management and

planning, despite the negative impact of forest progression in recent decades and the availability of scientifically-tested silvicultural models to adapt forest structure to habitat requirements of black truffle (Garcia-Barreda and Reyna 2013).

In recent years sustainability issues in public forests have been exacerbated by collective harvesting arrangements. As a result of decline in productivity, forests become economically unattractive to private harvesters, with municipality councils offering the floor price in auctions. Thus, every year residents interested in harvesting put their name down and share the rent. In Teruel province these arrangements increased from 30% auctions in 1992 to 63% in 2007, according to PTL information. This situation is usually coupled with an environment of weak law enforcement, thus encouraging extreme competitiveness among harvesters, overexploitation, excessive trampling and damaging picking techniques.

Wild *T. melanosporum* decline in Spain is not a unique case among edible fungi. In China, the native *T. indicum* is intensively harvested for commercial purposes since the late 1980s, when it was originally exported to Europe. Its price sharply increased and pure extractivism and damaging picking techniques have been indicated as the general rule (Wang and Liu 2010). Wang (2013) reported that harvests decreased by 30-50% in recent years, after about 30 years of intensive use, no harvesting regulation and no resource management.

Boa (2004) pointed out that high prices in commercially-harvested epigeous fungi promote overexploitation. However Yang et al. (2009) evaluated matsutake (*Tricholoma matsutake* Singer) harvesting in Yunnan (China) and showed that the type of harvesting access rights, the degree of regulation enforcement and institutional frameworks encouraging locally-rooted and innovative strategies were also key factors in the outcome of management practices. In our case study, it would be interesting to test if forests with contrasting regimes for truffle exploitation (e. g. private forests harvested by the landowner against private and public forests exploited by private harvesters) currently show differences in truffle yields and response to

management practices aimed at improving yields. However the official statistics available do not allow reliable comparisons of yields between public and private forests. In recent years ASY data are disaggregated into private and public forests, but some regions do not submit estimations and there is apparently no systematic methodology behind this estimation.

In conclusion, departure from the desirable regime of resource use poses important issues for sustainability of black truffle harvesting in Spain. These social and political issues need to be addressed to develop desirable ecological scenarios for black truffle. Strategies for sustainable use of wild truffles in Spain are discussed below, with a focus on legal, regulatory and policy measures.

3.3.1 Strengthening property rights

Poaching and trespassing decrease value of property rights over truffle. They are major issues in public and private forests of many areas where experienced harvesters are abundant. Wild *truffières* (i.e. forest stands where truffle fruits associated to particular host trees) are generally scattered throughout large forest areas with poor accessibility, thus making law enforcement difficult and costly, rendering ineffective the deterrent effect of forest rangers patrolling the area and making fencing an unreasonable alternative.

The most effective solution to poaching would be a coordinated effort of forest rangers, state security forces, landowners and private harvesters to increase surveillance and arrest poachers. According to Spanish Civil Code, a landowner must file criminal charges to claim stolen properties and a legal proceeding is required. In the case of public forests with truffle harvesting included in regional annual operating plans, poaching constitutes an administrative offence, thus making the claim process easier (Medrano-Ceña et al. 2011). The enforcement capacity of this approach largely depends on the price at which stolen truffles are valued by judicial or administrative authorities and on the valuation of the loss of future harvests due to

the damage caused to *truffières*. Comprehensive valuations require awareness and collaboration of state security forces and administration officials. Official statistics on truffle price could be helpful in this regard. ASY and ITSY currently include data on the economic value of truffle harvests. However ITSY data also include other truffle species with much lower prices, whereas ASY estimations vary greatly from region to region, with some of them using market prices and other ones using rents from truffle leases (as revealed by comparison with recent PTL data in Castelló province).

Some regions seek to undermine the legal position of poachers by banning harvesting of truffles at night or by regulating the possibility of signposting forests with reserved harvesting rights (Supplementary Material: Table S1), although the latter is rather seen by landowners as a way to attract poachers' interest.

Other social actions, such as associationism and cooperation among harvesters could help to discourage poaching and opportunistic behaviors, particularly if these organizations had enforcement capabilities or institutional support to promote professionalism and self-monitoring (Tedder et al. 2002).

In order to promote harvester professionalism and exclude poachers, Catalan regulation was pioneer in Spain in requiring administrative license –besides landowner's permit– to harvest truffles. In this region, only licensed harvesters and harvesters' associations are authorized to sell fresh truffles. However no license system has been implemented in any other region, thus making this regulation rather ineffective.

In addition to coordinated effort among regional governments, effective implementation of a license system would require an effort to explain such policy to harvesters, accustomed to work without administrative control. Involvement of harvesters could be greater if costs (taxes and administrative procedures) were exceeded by benefits, with Catalan regulation pointing to reinvestment of taxes in forest improvement works. Institutional support for

formalizing wholesale and retail truffle markets such as those in Barcelona (Llotja de Vic) and Huesca (Mercado de Graus) could also increase effectiveness of license systems, since agrifood companies are already obliged to record purchased amounts of truffles and to identify suppliers by Spanish law on health conditions for mushroom marketing (30/2009). On the other hand, broadening of use rights for private harvesters could help to involve them in the sustainable use of leased forests with low yields. Increased lease duration would reduce risks linked to large year-to-year fluctuations in harvest due to weather conditions and would increase trust between landowner and harvester. Enlarging the size of auctioned forests, i.e. merging several nearby forests with low truffle yields in a single auction, could be an interesting strategy to make public forests more attractive to private harvesters.

3.3.2 Rationalization of harvesting pressure

A scientifically-designed monitoring is the basis for assessing implications of intensive harvesting on long-term sustainability of wild fungi harvests (Pilz and Molina 2002). However no scientific information on truffles is available. Egli et al. (2006) and Luoma et al. (2006) found that careful harvesting techniques did not alter future harvests of epigeous mushrooms, although trampling and forest floor removal had a negative effect. But unlike epigeous fungi, some top soil removal is always required for harvesting truffles, and truffle spores remain completely encased in the sporocarp when it is ripe, so that harvesting removes them all from the soil and undermines spore dispersal.

In forests leased for truffle harvesting, fine-tuning of harvesting arrangements and lease agreements could help to reduce harvesting pressure or its impact. Forest management plans and lease agreements should consider either incorporating spores into soils of *truffières* or limiting the amount of sporocarps harvested (e. g. by bringing forward the end of harvesting season or by periodically leaving truffle unharvested during complete seasons). Since no

scientific information is available on the inoculum amount required for supporting sporocarp production, these actions should follow an adaptive management approach.

More drastic measures such as including annual quota volumes in lease agreements or establishing temporary moratoria on harvesting seem unwise in most public forests, because it would be difficult to check the degree of compliance of harvesters. Access to public forests is not usually controlled or limited and harvesters have no legal obligation to declare harvested or sold volume. Under such conditions, this measure would probably promote mistrust between landowners and harvesters, an increase in poaching and it would require a costly increase in control of circulation throughout forests.

3.3.3 Forest planning

Silvicultural practices can affect habitat for wild fungi (Pilz and Molina 2002; Garcia-Barreda and Reyna 2013). Considering the potential economic contribution of black truffle to Spanish forests and the currently scarce profitability of Mediterranean timber and NTFPs, forests would benefit from integrating this production into multifunctional forest management plans (Croitoru 2007; Palahi et al. 2008). Truffle use is easily compatible with most forest productions, since *truffières* and works of habitat rehabilitation for truffle typically take up only a small portion of the forest surface (Garcia-Barreda and Reyna 2013).

The Catalan regulation is the only one currently establishing that forest management plans should protect *truffières* from soil disturbance and logging of host trees. However this is difficult to implement because practitioners should be aware of *truffières* location, which most harvesters are reluctant to reveal.

Integration of truffle use in forest management would have a greater chance of success if local harvesters were involved in the design and monitoring of management plans, in consideration of their experience and knowledge of local environment. Framework agreements on

collaboration between harvesters' associations and forest owners' associations could help to build trust between these groups in order to develop specific forest management plans (J. Alhama, personal communication).

Public forest owners could encourage habitat rehabilitation projects by allowing private harvesters to propose and execute desirable silvicultural treatments. Terms and conditions of auctions could positively discriminate in favor of economic bids including silvicultural work carried out by harvesters as part of the rent. Degree and quality of execution would be relatively easy to check by the landowner and could be included as appraisal criteria in the following auction, making it easier that harvesters involved in sustainable use renew leases.

Forest certification could be an attractive option to promote forest planning and truffle traceability by linking sustainable truffle harvesting to enhanced marketing. However no specific standards for wild truffle certification are currently available.

3.3.4 Involvement of public stakeholders

Regional governments are nowadays the main regulatory authority for wild edible fungi in Spain and together with local entities are major forest owners (SGAPC 2014), thus responsible for the management of an important proportion of Spanish wild truffle.

Public forest owners enhancing their role as proactive and exemplary forest managers could help to advance in the conservation of wild truffle. Improving knowledge about truffle among officials in charge of forest management would help to encourage habitat rehabilitation projects and harvesting pressure control. Public forest managers often lack expertise on truffle ecology and information on the actual value of harvests, sometimes even being unaware whether yields are increasing or declining in the forests they manage. Thus they do not perceive lack of management as a problem, whereas private harvesters are not willing to share

information because they are afraid of the floor price of auctions being increased and of competition from other harvesters.

Spanish state forest law requires that public use forests allocate 15% of operating income to forest conservation and improvement, with some regions such as Valencian Community extending this obligation to all public forests. However, in practice revenues from truffle leases have rarely been used to improve habitat for truffle fruiting or to increase truffle inoculum in soils.

A more formal administration of records from public forest at the property level, together with assessment of potential truffle yield in these forests, could help public stakeholders to appreciate benefits of wild truffle harvesting and to involve public officials in long-term sustainable management (Tedder et al. 2002). Improvement and harmonization of ASY estimation methodology could also be useful. Public officials tend to consider annual rents from leases as the actual value of truffles. Ideally official statistics should include accurate data on real wild truffle harvest and its market value.

On the other hand, the regulatory role of regional governments could be enriched by developing strong partnerships among regional governments, local entities and private stakeholders, especially if the latter are organized in associations (Ros-Tonen and Kusters 2011). Harvesters frequently justify their tendency to secrecy as fear of government using information for inappropriate regulations. Catalan regional government created a sectoral roundtable –currently inactive– as a tool to promote cooperation, information exchange and promptly addressing new issues. These partnerships could also mediate conflicts between harvesters and farmers in areas where agriculture intensification is severely damaging *truffières* located in the agriculture-forest interface (J. Alhama, personal communication).

4 Conclusions and perspectives

The analysis of statistical sources for Spanish truffle harvest indicates that FETT estimates show higher consistency than ASY and ITSY. Comparison of FETT estimates with PTL suggests divergent trends in recent years, with wild harvest still declining while national production seems to recover thanks to plantations.

In a business-as-usual scenario the decline of wild black truffle harvest is likely to continue and eventually make commercial harvesting economically unattractive. With no involvement of forest owners or harvesters in sustainable use and management, private harvesters resigning from leases may result in competitive collective harvesting or *de facto* open access situations, thus aggravating sustainability issues. Increase of truffle production in plantations could also alter the economic interest of wild truffle harvesting and exacerbate this process (Williams et al. 2014). Plantations are more frequently irrigated and tilled, generating a more stable supply of larger and better shaped truffles, leading to price differentiation by quality and thus damaging wild truffle reputation and price.

The review of historical socio-political context for wild truffle harvesting highlights the implications of current harvesting regulation and policy on sustainability. Truffle harvesting in Spain is overwhelmingly commercial and the institutional framework for its exploitation has never created a general scenario encouraging sustainability. Strengthening of property and use rights, rationalization of harvesting pressure, forest planning and involvement of public stakeholders are proposed as corrective measures. Measures consistent with participatory approaches, adaptive management and forest multifunctionality are preferred, with government restrained to regulatory and exemplary roles and to law enforcement.

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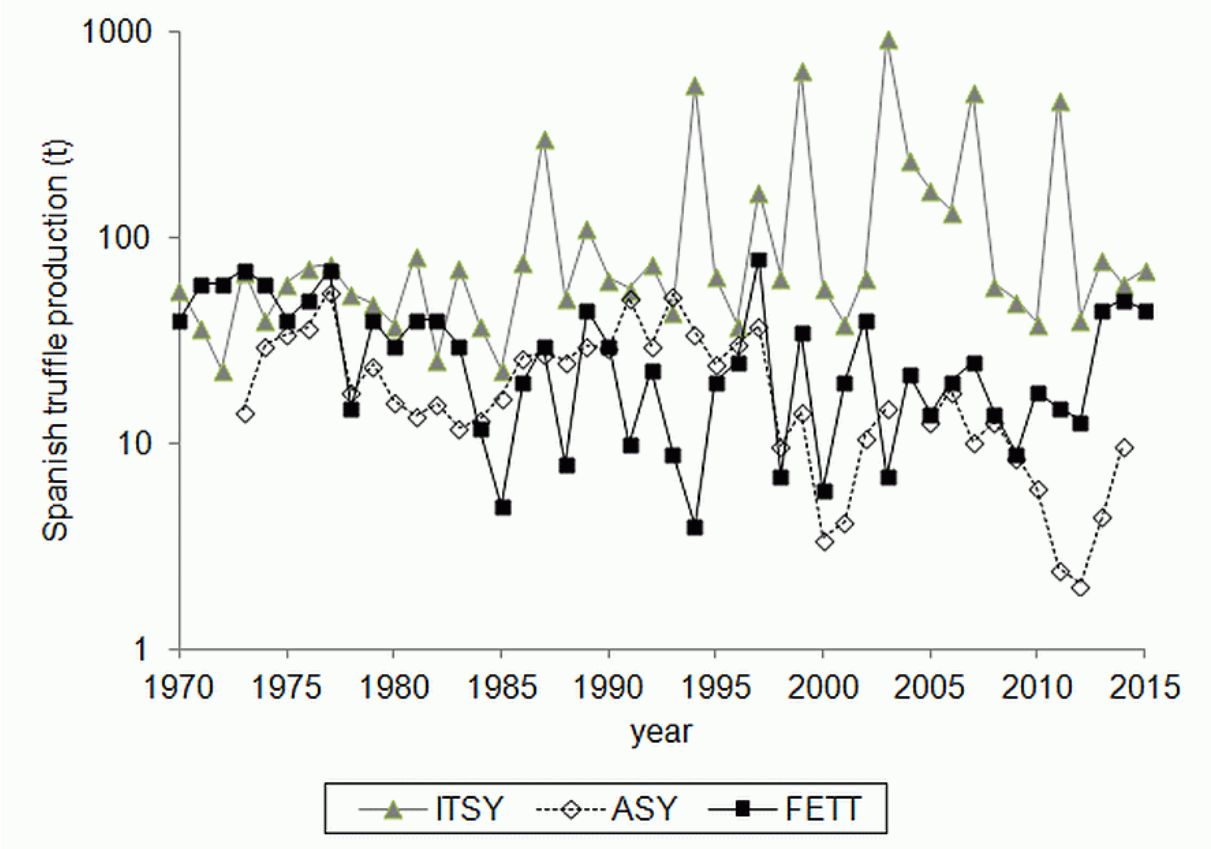

Fig. 1 Trends in Spanish truffle production according to several sources: International Trade Statistics Yearbook (ITSY), Agricultural Statistics Yearbook (ASY) and Spanish Federation of Associations of Truffle Growers (FETT). Note the logarithmic y-axis scale

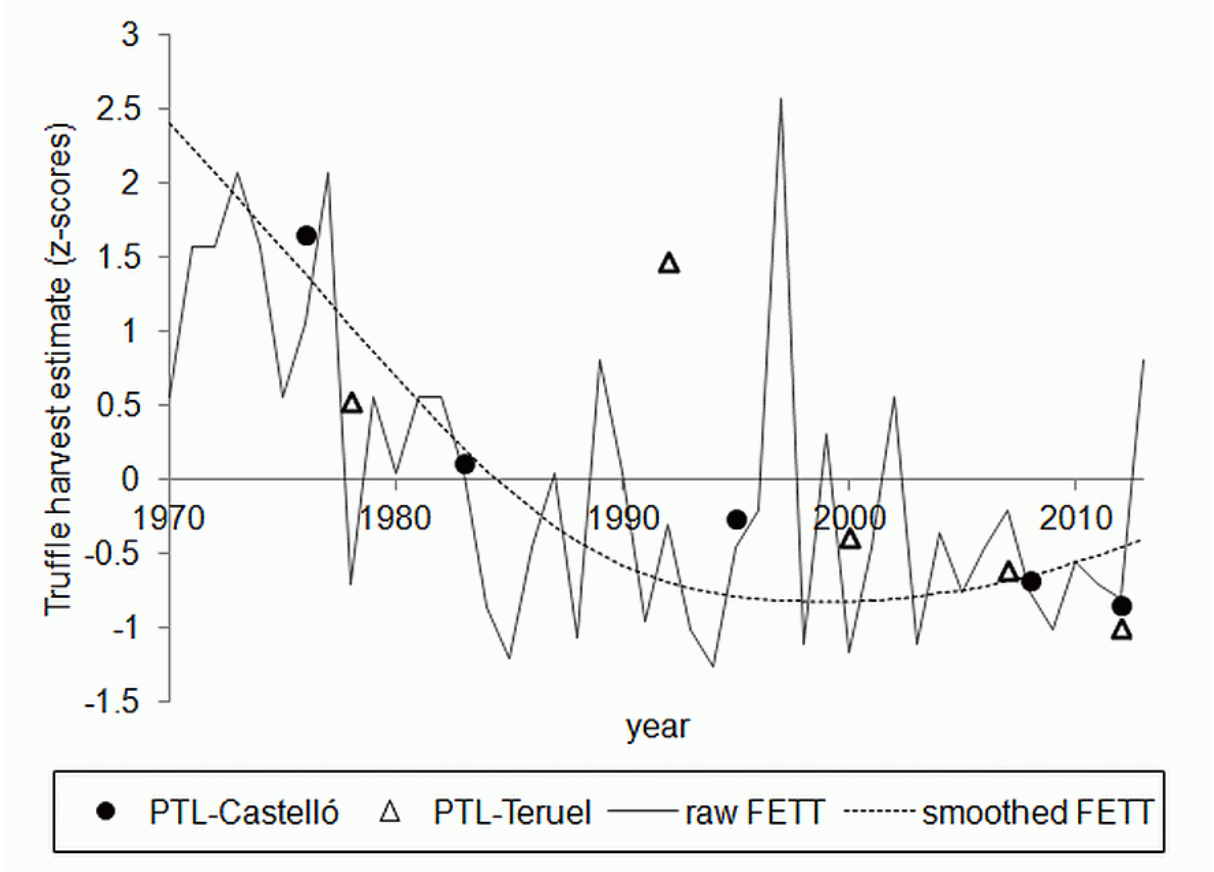

Fig. 2 Trends in rents from truffle lease agreements in forests under public administration in Teruel and Castelló Spanish provinces (PTL), raw estimates of Spanish black truffle production according to Spanish Federation of Associations of Truffle Growers (raw FETT) and FETT estimates smoothed with cubic splines and ring-width indices (smoothed FETT)

Table 1 Official statistics for Spanish truffle harvest analyzed in the present study

Data set	Statistical source	Available dates	Variable analyzed	Frequency/Time basis
ITSY	Trade Statistics Yearbook	1969-2015	Weight of truffles exported worldwide (pooled fresh and preserved truffles). It includes wild and cultivated truffles	Yearly, calendar years
ASY	Agricultural Statistics Yearbook – Forest Statistics Yearbook	1973-2014	Estimated weight of truffles harvested in the wild	Yearly, in practice harvesting seasons [a] (probably)
FETT	Spanish Federation of Associations of Truffle Growers	1970-2015	Estimated weight of *T. melanosporum* harvested (pooled wild and cultivated)	Yearly, harvesting seasons [a]
PTL	Departments of the Environment of Aragon and Valencian Community	For Teruel: 1978, 1992, 2000, 2007, 2010-2012 For Castelló: 1976, 1983, 1995, 2008-2012	Annual rents from lease agreements for *T. melanosporum* harvesting in forests under public administration in Teruel and Castelló provinces	Yearly, harvesting seasons [a]
$ITSY_{dec\text{-}feb}$	Trade Statistics Yearbook	1995-2015	Weight of fresh truffles exported worldwide from December to February	Monthly

[a] Harvesting season runs from November to March

Table 2 Pearson correlation coefficients (r), level of significance (P) and sample size (n) among the analyzed official statistics

	ITSY	ASY	FETT	PTL_{Teruel}
ASY	r = -0.09			
	P = 0.56			
	n = 41			
FETT	r = -0.20	r = 0.26		
	P = 0.18	P = 0.10		
	n = 46	n = 41		
PTL_{Teruel}	r = -0.35	r = 0.96	r = 0.34	
	P = 0.44	P < 0.001	P = 0.45	
	n = 7	n = 7	n = 7	
$PTL_{Castelló}$	r = -0.13	r = 0.88	r = 0.97	- [a]
	P = 0.76	P = 0.004	P < 0.001	
	n = 8	n = 8	n = 8	

[a] Correlation coefficient was not calculated due to the low sample size (n = 3)

Table 3 Pearson correlation coefficients (r), level of significance (P) and sample size (n) of the analyzed official statistics with ring-width indices and exports of fresh truffles from December to February ($ITSY_{dec\text{-}feb}$)

	ITSY	ASY	FETT
Ring-width indices	r = -0.11	r = 0.30	r = 0.67
	P = 0.47	P = 0.06	P < 0.001
	n = 44	n = 40	n = 44
$ITSY_{dec\text{-}feb}$	r = 0.09	r = 0.73	r = 0.77
	P = 0.70	P = 0.001	P < 0.001
	n = 19	n =17	n = 19

SUPPLEMENTARY MATERIAL

Table S1 Current legal regulation of wild truffle harvesting in Spain

Administrative level	Title
National[1]	Decree No. 1688/1972, of June 15, regulating winter black truffle hunting [1] Order of November 8, 1972, establishing the rules concerning the enforcement of Decree 1688/1972, of June 15 [1]
Regional (Aragon)	Order of November 10, 1998, regulating winter black truffle hunting in Government of Aragon forests and public use forests
Regional (Castile-La Mancha)	Order of September 3, 1986, establishing the harvesting season and regulating the hunting methods for winter black truffles
Regional (Castile and Leon)	Order of October 29, 2001, establishing winter black truffle hunting methods
Regional (Catalonia)	Law 6/1988, of March 30, on Forests of Catalonia Order of July 11, 1991, establishing the Sectoral Roundtable for truffles Order of July 15, 1991, regulating the truffle sector Order of August 9, 1994, amending Order of July 15, 1991 Order MAH/328/2005 of July 13, amending Order of July 15, 1991
Regional (Valencian Community)	Order of September 11, 1998, regulating truffle harvesting
Local (Alava)	Foral Decree 121/1997, of December 23, from the Provincial Council, approving the regulation for the use of native truffles in the forests of Alava

[1] Currently applicable only to regions without regulation