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ORIGINAL PAPER

The importance of data mining for conservation science: a case study on the wolverine

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Abstract Assessing the scale of ecological changes that have occurred since the onset of the Anthropocene is challenging. One major problem is that of shifting baselines, whereby the norms we set for judging the state of species, populations, or ecosystems change over time due to incomplete information. Here we show how data mining can be used to fill some of the information gaps fueling shifting baselines. We used as example an elusive species, the wolverine (*Gulo gulo*), given that information gaps are so prevailing for such species. We applied the concept of data mining to search documents hosted on publicly accessible online repositories and found information about the historical occurrence of wolverines that allowed us to revise their historical range in eastern North America. We found 12 historical accounts attesting the presence of wolverines in various parts of the Maritime Provinces of Canada, of which 11 were new to contemporary science. According to our results, the eastern limit of the historical range of the wolverine should be extended to include the current jurisdictions of New Brunswick and Nova Scotia. Biological change is the central paradigm of species status assessments. We show that online repositories of public domain literature can now be critical sources of information to assess biological change, including in the case of elusive species. Data mining constitutes a productive tool to uncover useful knowledge hidden in a sea of digitized historical information, and should thus allow researchers and conservationists to more effectively mitigate the problem of shifting baselines.

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Introduction

Despite the consensus in the scientific community concerning the dominant influence of human activities on Earth's biodiversity, assessing the scale of the changes that have occurred since the onset of the Anthropocene is challenging (Steffen et al. 2007; Zalasiewicz et al. 2008). A major problem is that of shifting baselines, whereby we fail to properly assess the historical state of biodiversity. The first manifestation of the problem occurs when we fail to integrate available historical information (McClenachan et al. 2012), and established baselines can continue to shift when a succession of scientists working on the same topic have different knowledge concerning the studied species, populations, or ecosystems (Pauly 1995). This leads to a shift towards the perception of a "new normal", which can be markedly different from the state of the system prior to the advent of considerable human influence.

Distribution patterns of species are prone to shifting baselines (Pauly 1995; Loring and Spiess 2007; Clavero and Villero 2014). A species' distribution is often a key determinant of its conservation status, because it is determined by its spatial variation in abundance (Brown 1984; Lawton 1999). The configuration of a species' distribution, such as whether it is continuous or fragmented, may reveal underlying processes such as extirpation events and responses to environmental stresses like habitat loss (Virkkala et al. 1993). The knowledge of overall configuration and extent of past distributions is now central to the development of species distribution models (Hortal et al. 2008; Elith and Leathwick 2009), as it helps to identify underlying processes driving current changes and to forecast future occurrences. However, knowledge of past distribution is fragmented, especially when species are elusive, hence the need to integrate new sources of information to increase the accuracy of the historical range of most species.

Determining if species are declining or increasing is a key criterion for assessing their conservation status (e.g. COSEWIC 2003; Abramov et al. 2009). To do so, biologists must produce accurate depictions of historical and current species distributions (e.g. Clavero and Hermoso 2015). Determining the presence of a species in space and time is prone to false negatives due to lack of information, especially historical information. Constructs of historical distributions are thus often uncertain (e.g. COSEWIC 2003). In this context, one growing concern is that scientists are not accessing all of the relevant information available to them. In particular, some information which used to be difficult and time consuming to retrieve, such as old scientific literature, literature produced by historians, and collections of specimens in museums, may often be overlooked. Yet digitized historical documents are increasingly shared in the public domain, which might open opportunities of very high value. Here we show the potential use of data mining (i.e. the discovery of interesting knowledge from large amounts of data; Han et al. 2011) as a way to fill information gaps at the root of shifting baselines.

We used the wolverine (*Gulo gulo*) in eastern North America as a case study to determine whether data mining can yield useful results for rare and elusive species, hence putting the method to the test. This species is particularly susceptible to false negatives because it occurs in low densities and is difficult to monitor (Golden et al. 2007).

According to the extensive 2014 status update report of the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), which was based on a large literature review and considerable arbitration by peers, wolverines were not reported to have ever existed in the present-day jurisdictions of Newfoundland, Nova Scotia, and Prince Edward Island (COSEWIC 2014). The eastern limit of the wolverine's historical range was determined to be in New Brunswick, and different works limit its presence either to the western (Banfield 1974), the northern (Seton 1909; van Zyll de Jong CG 1975), or the northwestern part of the province (COSEWIC 2003, 2014). Recently, Forbes et al. (2010) questioned the evidence suggesting wolverine presence in New Brunswick during the eighteenth century. Therefore, the proposed eastern limit of the wolverine's historical range remains uncertain.

Large herbivores such as caribou (*Rangifer tarandus*) and moose (*Alces alces*), typically constituting the main part of the wolverine's diet (e.g. Dijk et al. 2008; Dalerum et al. 2009), were historically present throughout the Canadian Maritime Provinces of New Brunswick, Nova Scotia, and Prince Edward Island (Haliburton 1829; Adams 1873; Harvey 1926; Gwyn 2003). We are aware of no factor which could have limited the range of wolverines in this region, especially given that the grey wolf (*Canis lupus*), another important predator of caribou and moose, was present historically throughout the region (Chamberlain 1892; Harvey 1926; Scott and Hebda 2004). To determine if the eastern limit of the wolverine's historical range should be revised to include all of the Maritime Provinces, we tested the prediction that historical records of wolverine presence exist throughout the region.

Materials and methods

Searching for relevant documents

We applied the concept of data mining to search for evidence of the historical presence of wolverines in the present-day Canadian Maritime Provinces. We accomplished this in two steps. First, we used Google's webpage crawling and indexing technology to search targeted sources of online content for relevant documents about our study area (Brin and Lawrence 1998). Our search queries targeted public domain historical literature on Internet Archives (http://Archives.org), a non-profit organisation with a stated mission of "universal access to all knowledge" (Internet Archives 2004), which implies building and managing a large and growing repository of textual documents, multi-media files, and web page content. It also hosts digitized documents from other organisations (e.g., Biodiversity Heritage Library, Natural History Museum, Project Gutenberg, Google, Microsoft, university and public libraries).

On Google's search engine, we used the keywords "Internet Archive" and various combinations of the following words separated by commas: Acadia, Acadie, animals, animaux, Cape Breton, Eastern Canada, fauna, faune, histoire naturelle, Île-du-Prince-Édouard, Île Royale, Île Saint Jean, Île St Jean, mammals, mammifères, natural history, naturalist, naturaliste, nature, New Brunswick, New France, Nouveau-Brunswick, Nouvelle Écosse, Nouvelle France, Nova Scotia, and Prince Edward Island. We also included the various words used to name the wolverine (see following section) to help find relevant documents during this first step.

Our data mining also led to the identification and consultation of archival holdings at the Centre d'études acadiennes Anselme Chiasson at the Université de Moncton (Charles-Robin Fund #521).

Searching for accounts of historical wolverine presence in documents

In the second step, we processed large volumes of text in retrieved documents using keyword searches in web browsers (for html conversions of scanned historical documents hosted on Internet Archives) and in Adobe Reader (for PDF files). An estimated minimum of 10 million words were processed during this procedure. We then used the following words to search for wolverine mentions: blaireau du Labrador, blaireau du Canada, carcajou, diable des bois, glouton, glutton, *Gulo aubudoni, Gulo gulo*, *Gulo luciis*, *Gulo luscus*, *Gulo vulgaris*, *Incles labradorica*, indian devil, quincajou, quinquajou, kinkajou, wolverene, and wolverine. The term "quincajou" and its variants do not refer to the South American animal *Poto flavus*, as early French writers (Denys 1672a; Le Clercq 1692) also used the term to name the wolverine (Ganong 1910). We also performed searches using the first or last few letters of these terms, because errors in the conversion of scans into digital characters sometimes yielded false negatives, especially for literature from the seventeeth and eighteenth centuries.

Results

We found multiple accounts attesting to the historical presence of wolverines in the Maritime Provinces of Canada (Table 1; Fig. 1). The species was considered to be absent from Prince Edward Island but present in New Brunswick during the middle of the nineteenth century (Sutherland 1861). By the end of that century, several authors listed the wolverine as absent or extirpated from New Brunswick (Tyrrell 1888; Chamberlain 1892). For Nova Scotia, Gwyn (2003) interpreted that wolverines were extinct by the end of the eighteenth century, while Dawson (1848) in his time considered it to be rare.

Discussion

Critical analysis of historical presence of the elusive wolverine

Our data mining of documents in the public domain uncovered considerable *prima facie* evidence of the historical presence of wolverines in the Maritime Provinces of Canada. This evidence, however, needs to be critically analyzed. For New Brunswick, the eight wolverine furs acquired by Simonds and White between 1764 and 1774 (Table 1, account 3) were already known to scientists (Squires 1968; Forbes et al. 2010). However, Forbes et al. (2010) suggested these furs could come from regions north of the Saint Lawrence River (Quebec), closer to a more recent historical distribution (Slough 2007). This is unlikely because local settlers and natives along the Saint John River (Fig. 1) were the main clientele of Simonds and White (Raymond 1905), and that region is the historical settlement region of the Maliseet, which were more active in the fur trade than the Mi'kmaq at that time (Gwyn 2003). Descriptions by Gyles (1736) also confirm wolverine presence along the Saint-John River (Table 1, account 2).

Table 1 Historical accounts of wolverine presence in the Maritime Provinces of Canada

Account no.	Province	Date or period	Site or region	Nature of information on wolverine	Reference
1	NB	1676–1677	Northeastern NB	Mentioned as being present	Le Clercq (1692)
2	NB	1689–1698	St.-John River	Snow track observations; behavioral descriptions; listed as trapped and hunted by the Maliseet along the St.-John River; descriptions of problems caused by wolverine at settlements and camps	Gyles (1736)
3	NB	1764–1774	St.-John River	8 furs acquired by Simonds & White (based at Portland Point) and exported to New England	Raymond (1898)
4	NB	1767	Northeastern NB	2 furs acquired by Robin, Pipon & Co[a]	Charles-Robin Fund #521
5	NB	1768	Caraquet	1 fur acquired by Robin, Pipon & Co	Robichaud (2009)
6	NB	1775–1783	St.-John River	6 furs acquired by Hazen & White (based at Portland Point) and exported to London	Raymond (1905)
7	NB	late 1800s	Dorchester	Undated report of a captured individual	Gilpin (1872)
8	NB	1850s	NB	Wolverines mentioned as present but rare[b]	Monro (1855)
9	NB	1860s	NB	Wolverines mentioned as occasionally observed until that period	Chamberlain (1892)
10	NS	1668	Saint-Pierre	Mentioned as present; behavioral descriptions; predation on a heifer attributed to wolverine	Denys (1672a)
11	NS	1700	Wolfville (Port-Royal)	Mentioned among animals harvested by natives	Diéreville (1708)
12	NS	1700s	Peninsular NS and Cape Breton	Unknown number of furs exported to London	Gwyn (2003)

Accounts were found through data mining of digitized public domain literature (*NB* New Brunswick, *NS* Nova Scotia) and are mapped in Fig. 1

[a] The 2 furs were listed in an end-of-year tally, with fur acquisitions coming from a series of landings along the New Brunswick coast

[b] This mention by Monro (1855) is based on information provided by naturalist George Augustus Boardman (McAlpine 1994), which was mostly active in the St. Croix River area of New Brunswick (Boardman 1903)

All other historical accounts reported in our paper appear new to contemporary science. Some are additional historical fur harvest accounts (Table 1, accounts 4–7, 12), while others are mentions of the species' presence (Table 1, accounts 1, 8–11), or descriptions of events involving wolverines (Table 1, accounts 2, 10). With no specimen or photograph

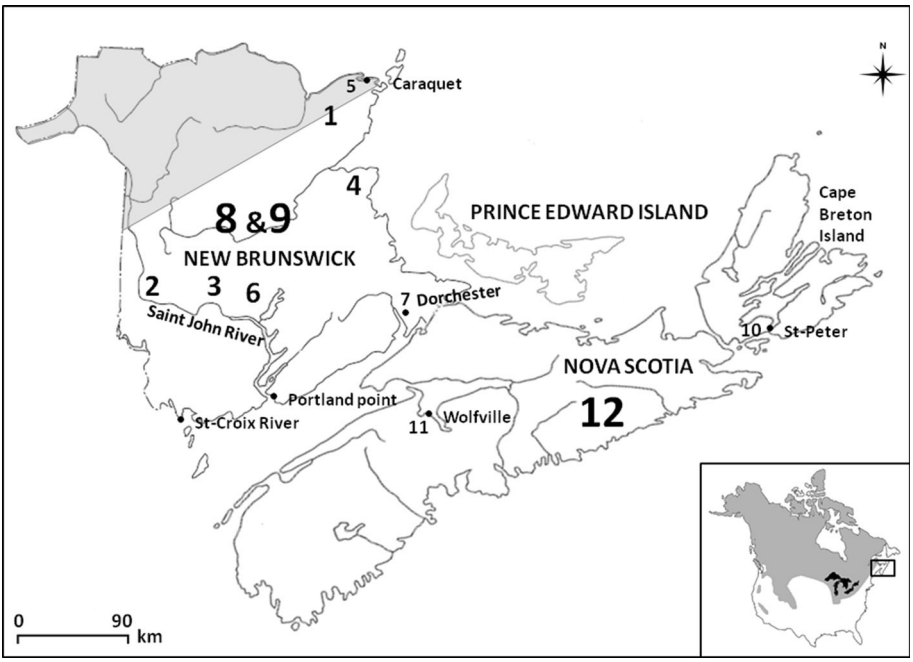

Fig. 1 Locations in the Maritime Provinces of Canada associated to the historical presence of wolverines. Each historical account is identified by a reference number (see Table 1) and referred to an entire present-day jurisdiction (*large numbers*), to a general area (*medium-sized numbers*), or to a specific location (*small numbers*). The *shaded area* represents the southeastern limit of the historical distribution of wolverines in Canada according to COSEWIC (2014)

available, these accounts constitute the strongest body of evidence compiled to date in support of the historical presence of wolverines in New Brunswick and Nova Scotia.

We found fewer evidence of the historical presence of wolverines in Nova Scotia than in New Brunswick (Table 1, accounts 10–12), and no evidence at all for Prince Edward Island. Nova Scotia and Prince Edward Island are less connected to the rest of the continent than New Brunswick, and while wolverines were indeed trapped by natives in Nova Scotia (Diéreville 1708), the species may have always been rare there. That New Brunswick was historically the main source of furs in the region supports this interpretation (Gwyn 2003; Griffiths 2005). An alternative interpretation is that wolverines had been extirpated earlier in Nova Scotia and Prince Edward Island, following the decimation of large gregarious herbivores that usually constitute their main food base (e.g. Dijk et al. 2008; Dalerum et al. 2009). Indeed, caribou were already rare on Prince Edward Island in the seventeeth century due to hunting pressure by natives (Denys 1672b), and they had disappeared from the Island by the time Adams (1873) described the natural history of the Maritime Provinces. Caribou were considered to be on the verge of extinction by 1872 in Nova Scotia (Gilpin 1872), whereas the last reported caribou observation in New Brunswick may date from 1928, north of Nictau Lake (Parker 2004). Moose were absent from Prince Edward Island according to Denys (1672b). The moose population in Cape Breton Island appeared to have been severely reduced by natives equipped with muskets in the seventeeth century (Denys 1672b), and an influx of immigrants to the Island led to the mass hunting of moose for their hides in the late eighteenth century (Haliburton 1829). By the middle of the nineteenth

century, moose were considered to be in danger of extinction in Nova Scotia (Gwyn 2003). In New Brunswick, concern for the declining moose population led to the adoption of legislation to limit the moose hunting season in 1850, and to its closure in 1937 (Squires 1968; Parker 2004). Finding additional accounts of wolverines for Prince Edward Island and Nova Scotia could entail searches in literature from the sixteenth century, when Basque fishermen had frequent contact with the Mi'kmaq (Bakker 1989).

In summary, data mining indicates that wolverines were historically present in New Brunswick and Nova Scotia during the early contact period with European settlers in the seventeeth century, but that they may have been absent from Prince Edward Island. This suggests we need to modify the historical distribution of the wolverine in North America, to include New Brunswick and Nova Scotia.

Data mining of historical information

There are several recent examples of integration of historical information to adjust baselines on species distributions (e.g. McClenachan et al. 2012; Clavero and Delibes 2013; Clavero and Hermoso 2015). Loring and Spiess (2007) used nineteenth century accounts of naturalists, explorers, and fur traders to adjust the baseline distribution of the grizzly bear (*Ursus arctos*), thereby confirming its historical presence in northern Quebec and Labrador. DiNatale (2014) used the distribution of ancient fish salting plants and coins to determine the distribution of Atlantic bluefin tuna (*Thunnus thynnus*) between the sixth century B.C. and the fifth century A.D. to demonstrate that the species was once numerous in the Black and the Azov seas. Our study clearly shows the potential of unearthing historical information from large online repositories of digitized historical documents that are integrally searchable.

While we used a rare and elusive species to demonstrate the extent of the potential of using data mining of historical information to improve historical distribution assessments, the method can be easily applied to any mammalian species that was commercially trapped for their fur, and therefore of acute interest to historical human societies. Trees and many other plants, often being critical natural resources to humans, are also well represented in early historical texts, as can be seen for eastern North America (Denys 1672a; de L'Hermite 1970). Freshwater and marine fauna (e.g., anadromous fish, demersal fish, mollusks), are also historically important resources and therefore frequently mentioned in historical texts (Denys 1672a, b; de Bougainville 1861; Ganong 1887). Therefore, the ease with which historical texts can now be accessed could shift the baseline distribution of a considerable portion of earth's biodiversity, ranging from marine macrofauna to terrestrial plants and vertebrates, and involving species much easier to work with than wolverine.

The potential of data mining to produce highly relevant information to conservation science has been recently demonstrated by Proulx et al. (2013), who determined from data on internet search queries, phenological events such as mosquito outbreaks and pollen blooms, as well as the current distribution of invasive species. Recent works on the baseline distribution and status of socioeconomically important species also used data mining to produce useful information from large amounts of data (e.g. Clavero and Hermoso 2015; Clavero et al. 2015; Clavero 2016) In our study, we showed that data mining can even unearth critical historical knowledge about elusive and low density species with relative ease. Large amounts of literature have yet to be digitized or made available on the internet, therefore publically accessible repositories of textual records will continue to grow. As more scientists tap into this kind of information, our ability to assess the changes that have occurred since the advent of the Anthropocene should greatly improve.

The value of data mining to produce useful information for conservation science is clear. However, there are hurdles to overcome in order to improve the practicality of applying this tool on a larger scale. There is considerable variability in the quality of contributions to digitized historical texts in online repositories. Contrary to long-established contributors like Project Gutenberg (Hart 1992), large-scale digitization endeavours by entities such as Google, Microsoft, and Internet Archive do not appear to be accompanied by proof-reading of digital conversions. While PDF files of historical documents can be of high esthetic quality, character recognition and keyword searches may be very poor, and this also hinders the performance of engines like Google, which are able to crawl the content of documents stored on servers. The number of errors that end up in digital texts during the scanning process ranges from negligible for relatively recent documents, to considerable for very old texts using particular fonts causing some letters to be systematically converted into the wrong digital character. Efforts to correct systemic errors originating from the scanning process will further improve our ability to apply data mining on a larger scale for old sources of documentation. Also, domestic search tools for repositories such as Internet Archive and Biodiversity Heritage Library perform poorly when using multiple keywords. Finding specific types of information for specific parts of the world is therefore difficult, unless users bypass these tools by using internet search engines based on crawling technology. Improving search tools offered to visitors of online repositories will allow them to quickly find the documents they need to target for data mining.

Conclusion

Data mining of historical information can increase the quality of species status assessments by establishing more accurate baselines. Such baselines are needed to determine whether a species' range or abundance changed sufficiently to justify a new status or reparative actions, because biological change constitutes a central paradigm of species status assessments (IUCN 2012; COSEWIC 2012). With the rise of large online repositories that are integrally searchable, more conservation and ecological restoration projects should be based on historical reference points (Balaguer et al. 2014; Clavero and Villero 2014; Clavero and Hermoso 2015). Data mining of historical information constitutes an addition in the toolbox of conservationists to manage biodiversity and the ecological integrity of ecosystems, by mitigating the problem of shifting baselines in the study of biological change.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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