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HOW CAN EPIDEMIOLOGICAL MONITORING AND MODELLING CONTRIBUTE TO MANAGEMENT DECISIONS? LESSONS LEARNED FROM TEN YEARS OF BRUCELLOSIS IN FRENCH WILDLIFE

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SUMMARY

Epidemiological monitoring and modelling are tools to inform management decisions. However, whether research actually feeds field actions depends on how actors from both fields interact. We propose a feedback on the outbreak of brucellosis due to *Brucella melitensis* detected in 2012 in the French Alps in humans, cattle and ibex. Based on changes in the category of papers published, we identified three phases in epidemiological knowledge: descriptive epidemiology was performed in 2012-2014, analytical studies in 2015-2020, and evaluative epidemiology emerged since 2021. Management phases followed knowledge with a one-year lag. However, changes in management decisions were not primarily related to changes in knowledge, but to the societal reaction to management and to the discovery of a new infected herd. Having identified the factors promoting or limiting the interaction between science and management, we propose several ways for improving the scientific approach and its use in health management.

INTRODUCTION

Evidence-based decision-making has become a general rule, in particular concerning health. Epidemiological research is intrinsically designed to play a central role in informing decision in health policies. Describing the importance and distribution of diseases, analysing their drivers and evaluating management actions are the main ways by which epidemiology helps improving health management. However, as in other fields, researchers may be frustrated by the inadequate use of science (Stephen, 2017). The way scientific knowledge is used by stakeholders to define or justify action is not straightforward, as the context plays a major role in the interpretation and the willingness to account for scientific evidence (Dobrow et al., 2004).

A first major aspect of the context of health management at the wildlife-livestock-human interface is the presence of numerous stakeholders, each focused on specific and sometimes conflicting issues. The main issues at stake are human health, livestock health and farming,

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wildlife health and conservation, and the economic consequences of each of them. Moreover, lack of knowledge, risk persistence, system unpredictability and limited feasibility of management operations in natural ecosystems make the appropriate use of evidence more difficult. Such situations require a adaptative management schemes, *i.e.*, a systematic approach for improving management by learning from management outcomes (Williams and Brown, 2016). In particular, the management cycle concerning wildlife diseases should ideally include risk assessment, definition of management objectives, action and evaluation of the action efficacy, all being performed in parallel with the monitoring of the outbreak and including all the relevant stakeholders (Portier et al., 2019). Adaptive management and wildlife disease scheme are both based on strong exchanges and a deep understanding between scientists and decisions makers. Here, we used the case of brucellosis in Alpine ibex *Capra ibex* to study how these exchanges were performed, and what were their outcome in terms of decision making.

While France was officially free of brucellosis since 2005, infection by *Brucella melitensis* was discovered in 2012 in the French Alps, around the Bargy massif. Infection was successively identified in humans (2 cases), in cattle (1 herd) and in local chamois *Rupicapra rupicapra* and Alpine ibex populations (Mailles et al., 2012, Garin-Bastuji et al., 2014). While seroprevalence was low in chamois (1/55 tested in 2012), high values were observed in ibex (close to 50% in females), which was an unprecedented situation in European wildlife (Garin-Bastuji et al., 2014). This specific context at the wildlife-livestock-human interface raised many issues. In particular France has been declared officially free from ruminant brucellosis after decades of efforts from farmers. Therefore, this group was strongly defending eradication in the wildlife compartment. On the other hand, nature protection associations highlighted the conservation of the Alpine ibex, a formerly highly threatened species now emblematic of nature conservation all over the Alps, and rejected any hypothesis of culling, especially without preliminary testing of animals.

Faced with this unprecedented situation, management scenarios had to be created at the same time as the process of knowledge acquisition, or even before. A combined monitoring of epidemiology, demography and spatial ecology was initiated in 2012. Each year, some ibex were captured and tested for the presence of brucellosis antibodies (laboratory analyses before 2015, field tests since then). Seropositive ibex were euthanized as part of management measures. Seronegative ibex were visually marked, some were equipped with VHF or GPS collars, and all were released and monitored. Population abundance was estimated through capture-mark-resight methods based on standardized counts of marked and unmarked individuals in the area, repeated several times per year, every year. Female reproductive success was estimated through the repeated observation of marked, known-aged females. Depending on the year, authorities chose management strategies that combined captures/test/removal of seropositive individuals and culling of individuals with unknown health status, with variations in the numbers of ibex, sex-age classes and areas targeted by each of them (Lambert et al. 2021). However, the application of these decisions was limited due to field constraints and to opponents performing field and legal actions, leading to differences between the policy makers' strategy and the action actually implemented in the field.

Ten years after the emergence of the outbreak, our objective was to determine the main management phases and to analyse the extent to which management decisions were driven by changes in the field situation, progress in the understanding of disease dynamics or other considerations. We also searched for ways to improve research itself and how to use the

results in order to improve decision-making. We particularly studied the role of epidemiological models and the ways modelling could be improved.

MATERIALS AND METHODS

We first described the progress of the outbreak in terms of field situation (ibex population size and seroprevalence of brucellosis), progress in epidemiological understanding of the outbreak (publications of international papers, reports from collective expertise) and main management measures (number of ibex captured and culled). Although the study of the system led to a continuous progress in the understanding of the outbreak epidemiology, we distinguished between descriptive, analytical (search for causes), evaluative (assessing the efficacy of management measures) or modelling epidemiological studies, since each type of studies brings distinct levels of information for management decisions. We also determined changes in management phases, corresponding to different trends in decision-making. Based on the authors perception and on meeting minutes, we tracked the main arguments that conducted to changes in management decisions and analysed how they were related to the field situation, to changes in general knowledge on disease epidemiology or other arguments.

RESULTS

Outbreak history

The Bargy massif is a small mountain chain (15 kilometres long) located in the Northern French Alps, Haute-Savoie. Based on the follow-up of GPS-collared females (that play a major role in brucellosis epidemiology – see below), five socio-spatial units were identified in 2015, and then grouped into two areas showing contrasted epidemiological patterns (Fig. 1).

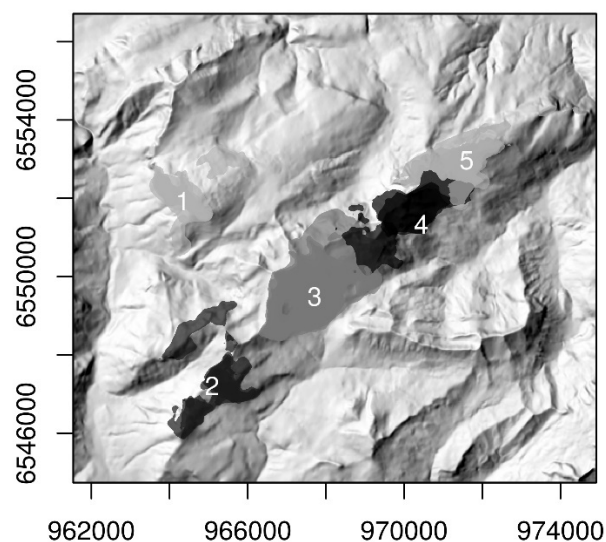


Figure 1. Socio-spatial and epidemiological structure of the Alpine ibex population in the Bargy massif (Lambert et al., 2020). Each coloured area represents the distributional range of a socio-spatial unit, as identified by the GPS monitoring of females, that play a major role in brucellosis epidemiology - see text. Socio-spatial units 1 and 2 correspond to the peripheral area, with low seroprevalence in 2013-2015, while units 3-5 constitute the core area, with high seroprevalence in 2013-2015 (Marchand et al., 2017).

The main results of the demographic and epidemiological monitoring are represented in Fig. 2, also with the progress in the knowledge and understanding of the epidemiological situation and with the management actions implemented. The ibex population, estimated to 570 individuals in 2013 (95% confidence interval: 487-660), sharply decreased following the massive culls in autumn 2013- spring 2014 and in 2015 (251 and 70 ibex culled, respectively). The population then increased to around 380 in 2018-2020 (no estimates are available for more recent years). Since 2013, seroprevalence decreased dramatically. While it was close to 50% in females of the core area, 35% in males of the core area and 15% in the peripheral area in 2013, seroprevalence decreased to 4-6% in 2022 (updated from Calenge et al., 2021). Other field discoveries include 2 cases in humans, 2 in cattle herds and 4 in chamois.

Three phases of knowledge and management

2012 – 2014 (knowledge) and 2012-2015 (management):

Papers published define three knowledge phases (Fig. 2). In 2012-2014, no prior information on the ibex population was available and only sporadic cases of brucellosis had been identified before in other populations of ibex. The first publications described the emergence of the outbreak in humans and cattle (Mailles et al., 2012), the discovery of brucellosis infection in ibex and chamois (Anses, 2013, Garin-Bastuji et al., 2014), identified the strain circulating in ibex as *Brucella melitensis biovar 3* and attributed its origin to a spillover from domestic herds before the last bovine case in the area that occurred in 1999 (Mick et al., 2014). The first raw seroprevalence estimates were highest in male ibex aged more than 5 years old (Anses, 2013).

The management of brucellosis is regulated by laws concerning both the disease and the host. Brucellosis is a notifiable disease and its eradication is required according to European and national laws. On the other hand, Alpine ibex is considered as a near-threatened species in France and its protection status is guaranteed by international and national regulations. Decisions had to be taken following both regulation systems, that are handled by ministries of Agriculture and Environment, respectively. To capture or cull ibex, managers must ask the opinion of the Conseil National pour la Protection de la Nature (CNPN), an independent council managed by the ministry of environment. They may also rely on the scientific opinion arising from independent collective scientific expertise coordinated by the Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail (Anses), that may be sollicitated by ministries or other structures like associations. Both the CNPN opinion and the scientific opinion from Anses are consultative only, meaning that policy makers do not necessarily follow their recommendations.

During the first phase, management decisions were taken with virtually no information. After the first captures in 2012-2013, the situation was considered an emergency (Anses, 2017), and the methods applied were directly derived from management strategies used in domestic herds. The Ministries of Agriculture and Environment asked Anses to urgently provide a first scientific opinion in August 2013: conclusions were limited due to time constraints (only one month between the request and the due date) and lack of knowledge. Because ibex older than 5 years old were considered as the most probable sources of infection, due to their high apparent seroprevalence, the option taken by policy makers was to cull all ibex aged more than 5 years old, and in practice 251 were culled in autumn 2013 and spring 2014. During the cull, no information was collected on the culled ibex. The extent of

the operation alarmed the local and national nature protection associations. Awareness campaigns alerted public opinion against the cull and since then, both field and legal actions were taken each year when culls were planned.

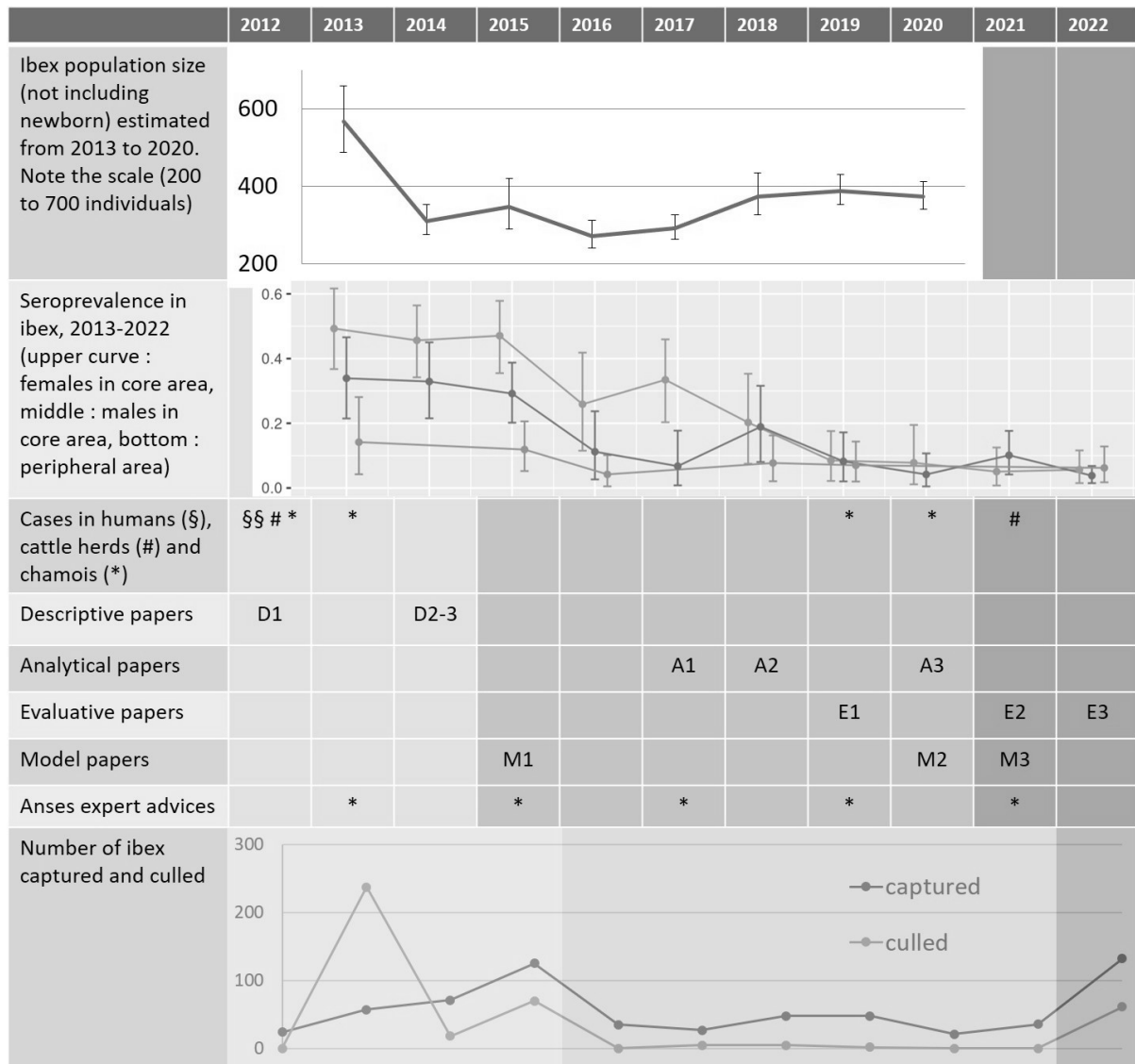


Figure 2. Calendar of the main field discoveries, progress in knowledge and management actions implemented. The main epidemiological studies are : D1 : Mailles et al., 2012, D2 : Mick et al., 2014, D3 : Garin-Bastuji et al., 2014, A1 : Marchand et al., 2017, A2 : Lambert et al., 2018, A3 : Quéméré et al., 2020, E1 : Ponsart et al., 2019, E2 : Calenge et al., 2021, E3 : Lambert et al., 2022, M1 : Thébault et al., 2015, M2 : Lambert et al., 2020, M3 : Lambert et al., 2021. The three phases of knowledge and management are identified by distinct shades. D = Descriptive; A = Analytical; E=Evaluative; M = Modelling.

In 2015, the paradigm of the “healthy core group” emerged. The proposed strategy was to intensively capture and test ibex and release the seronegative ones, followed by rapid culling of the remaining, untested animals. The idea was to keep a substantial group of ibex with known seronegative status to preserve the local population, while rapidly achieving eradication of brucellosis. This change of strategy was probably due to the difficulty in reaching all individuals in the field, because of topography and harsh meteorological

conditions, to lack of acceptability of massive culls and the absence of evidence of their efficacy. The method was implemented in 2015, however with uncomplete realization (125 captures, 70 culls), due to both difficulties to reach animals in the field and to the protest actions from nature protection associations who rejected the culls without preliminary testing of animals.

2015 – 2020 (knowledge) and 2016-2021 (management):

In 2014, nature protection associations asked Anses to design and evaluate alternative strategies for managing brucellosis in ibex. The working group worked for nine months, summarized previous knowledge and introduced management scenarios that were compared qualitatively and quantitatively using a first epidemiological model (Anses, 2015, Thébault et al., 2015). The model was based on the literature on demography and ecology of ibex, and on knowledge on brucellosis in domestic species, with a cost (impact on ibex population)-benefit approach (probability of extinction of brucellosis). The report also listed knowledge gaps, that were progressively filled during the following years. First, socio-spatial structure was identified as a strong determinant of brucellosis seroprevalence (these findings were first highlighted in 2015 and later published in Marchand et al., 2017), suggesting a contrasted disease dynamic between the peripheral versus the core area. The main routes of transmission were identified using serological and bacteriological investigations (Lambert et al., 2018) and the genetic structure of the population was investigated (Quéméré et al., 2020). In parallel with these investigations, an epidemiological model accounting for up-to-date knowledge was elaborated, analysed and used to unravel main routes of transmission and at-risk classes (Lambert et al., 2020) and to compare management scenarios (Lambert et al., 2021). Altogether, these studies concluded that transmission occurred mainly by exposure to infectious births and abortions, followed by venereal transmission. Females were the source of 90% of infections, while males played the role of disseminating infection between socio-spatial units. Specifically, socio-spatial units located in the core area of the massif (especially units 3 and 4, Fig. 1) were the source of transmission to other units (Lambert et al., 2020). As a consequence, management scenarios were predicted to be more efficient when targeting females, and especially young females, in the core area (Lambert et al., 2021).

Interestingly, management decisions were not synchronous with phases of knowledge but were delayed by one year. The second management phase thus lasted from 2016 to 2021. At this time, management strategies relied both on captures and culls, mostly targeting the core area, with 20-50 culls planned each year. However, nature protection associations consistently brought legal actions each year and justice generally suspended the culling operations (but not the captures) in emergency. On the other hand, farmers protested against this management strategy that contrasted with the whole culling of infected herds, which is mandatory in domestic ruminants. Finally, 215 captures and 12 culls were performed between 2016 and 2021.

Since 2021 (knowledge) and since 2022 (management):

An experimental assay of vaccination on captive ibex revealed a high risk of *Brucella* shedding in the environment (Ponsart et al., 2019). This information and the lack of evidence for ibex protection by vaccination precluded the use of vaccination for ibex (Anses, 2019). The management actions to be evaluated were thus test-and-remove and culling. In 2020, the amount of data generated also allowed to estimate adjusted seroprevalence accounting for the

high proportion of marked animals and the fact that most captures occurred on unmarked individuals. It also allowed determining the force of infection and its variation (Calenge et al., 2021, Lambert et al., 2022). These results suggested that the force of infection was divided by approximately 10 in 2015-2016, i.e. during management phase 2. This drop probably resulted both from management actions and natural changes in infection dynamics.

In October 2021, a new case of brucellosis was discovered in a large cattle herd, generating a strong reaction among farmers. Local and national authorities were asked to eradicate brucellosis as soon as possible, generating strong discussions. A new advice was asked to Anses by the ministries of Agriculture and Environment, with a very short delay (2.5 weeks). The request explicitly asked for the use of epidemiological models to compare six pre-defined management scenarios (Anses, 2021). The management strategy that was adopted by policy makers was again in line with the idea of a healthy core group, with as many captures as possible followed by the cull of all remaining unmarked animals. Finally, 135 captures and 61 culls were performed in 2022.

Arguments for change and factors limiting or promoting the science-decision interaction

Examining the arguments that conducted to changes in management decision, we identified that they relied both on new knowledge and on social reactions to field discoveries. Changes from phase 1 to phase 2 probably relied on the following elements: (1) the massive cull in 2013-2014 did not result in clear decrease in prevalence (Marchand et al., 2017), and some results suggested counter-productive effects (Lambert et al., 2022); (2) massive cull lead to strong reactions from nature protection associations, including legal actions, thus nearly precluding the use of culling during management phase 2; (3) no new case of brucellosis was observed in domestic herds or humans between 2013 and 2020. Between 2016 and 2021, the avoidance of protest by nature protection associations was probably a main argument for requesting limited numbers of ibex culls, with all decisions being taken to court and broken. The drastic change between 2021 and 2022 was clearly determined by the discovery of a new infected cattle herd and by the strong farmers reactions following this discovery and the whole culling of the infected herd.

Factors that we believe promoted or limited integration between science and decision are summarized in Table 1. In our opinion, five factors acted to better integrate science into decision. First, the Anses scientific opinions, although not mandatory, were read by most stakeholders and were used to build or to counteract management strategies. Confidence in Anses opinions relied on the fact that each of them was elaborated by an ad hoc interdisciplinary working group, fulfilling the rules of independent collective expertise. Anses groups were the main occasion for scientists to formally interact with requesters (Ministry of Agriculture or associations). Second, CNPN opinions also fed the debate, although exchanges with scientists working on brucellosis were limited. Third, institutions involved in the outbreak management included both research teams and field or laboratory actors. At the French Office for Biodiversity (OFB), contacts occurred between the local field agents and the national research group; in Anses, the expertise groups included agents from the Anses national reference laboratory for brucellosis in ruminants who conducted diagnostic on ibex. The personal knowledge and mutual acculturation among OFB or Anses groups contributed to exchanges between science and management action, and to exchanges between national and local actors. The first three factors lead to a fourth and fundamental aspect facilitating the use of science, which is interpersonal knowledge within and between the structures involved.

Beside the formal exchanges of group working on opinions, numerous informal interactions took place, including with decision-makers who directly asked to individual scientists to clarify specific points. These contacts contributed to the transmission of new results to decision-makers, often before Anses reports were elaborated. Finally, the ministry of Agriculture funded both management actions and research, which helped to design relevant research programs and to communicate research results to decision-makers.

Table 1. Factors limiting and promoting interactions between scientific advances and management decisions

Promoting interactions	Limiting interactions
1. Collective scientific expertise advices (Anses)	1. View of the crisis as an emergency and belief in rapid crisis resolution
2. Mandatory consultation of the council for the protection of nature (CNPN)	2. Opposed views on aim of the management, feasibility, efficacy and interest of tools
3. Structures mixing scientific teams and field/laboratory actors (Anses, OFB)	3. Divergent and untold ethical principles
4. Interpersonal knowledge between scientists, decision makers and field actors	4. Absence of place for discussion
5. Funding of monitoring and research by policy makers	5. Turnover of persons in charge
	6. Memory of previous situation or interpretation

On the other hand, we identified six factors limiting the use of research by policy makers. First, many stakeholders considered the situation as an emergency, during the first phase, and later for some of them. Most actors also considered that the issue could be solved rapidly, in 1-2 years. Scientific opinions were thus asked in very short time, which limited the possibility to integrate multidisciplinary and to consider long-term scenarios. The need for long-term research was not recognized before 2015 and the time frame for decision-making time was often too short to incorporate research results. This sense of emergency explained that no information was taken on culled ibex in 2013-2014, which precipitated the opposition of associations and deepened the crisis. Second, strong oppositions emerged concerning the aim of the management action and the feasibility, efficacy and cost-benefit of management tools. The first aim of farmers was to eradicate brucellosis, which included using massive culling of ibex, applying to wild populations the same principles that are used in livestock management of brucellosis. On the other hand, the first objective of nature protection associations was protecting the ibex was the first objective, thus no cull of ibex was conceivable, especially concerning non-tested animals. Moreover, mass media intervention often oversimplified, crystalized and stiffened positions of all actors, including scientists. Behind these oppositions, a third factor was the divergence about values that should be considered to manage the outbreak. Although not explicitly stated, principles of animal ethics (not killing and not harming) and/or environmental ethics (respecting ecosystem integrity, non-interventionism as a precaution) probably guided most of opponents against the culls, while ethical principles of public health (possibility of constraint to avoid damage caused to others, proportionality of means, Upshur, 2002) likely motivated the authorities in charge of managing the outbreak. Fourth is the absence of a place for discussion between scientists and decision makers, and among actors, i.e., local and national authorities from different ministries. During the most intense crisis times, interactions were distorted. Local politicians, farmer and association representatives directly solicited minister cabinets to defend their position, while services in charge of health policy were not involved in the discussions. Due to this lack of concertation, in 2015 and 2022, decisions were taken at the national and political level. Fifth, the

concertation was discontinued by the turnover of persons in charge in all public services at the local and national levels. Last, we observed that some stakeholders often set their mind on a first impression. For example, after the 2013 cull, raw seroprevalence in ibex aged less than 5 years old was higher than before cull. This was interpreted as a rebound of incidence due to social perturbation, with young males replacing old males for reproduction and being massively exposed. This interpretation was demonstrated to be erroneous, as the change in prevalence was instead due to sampling bias that were year-dependent (Marchand et al., 2017). However, the apparent rebound in prevalence is still considered to have occurred by some actors. The massive cull of 2013 and 2015 also conducted some stakeholders to consider that management was mainly based on massive culling, even after several years with few or no cull.

DISCUSSION

“Wildlife Health 2.0 research teams will need to be as adept at providing the scientific justification for options to respond to wildlife health threats as they will need to be in producing the social evidence to identify implementation strategies that are feasible, sustainable, understandable, and acceptable to decision makers” (Stephen, 2017). The case of brucellosis in ibex offered us the occasion to apply this recommendation and to propose ways to improve science-based management, a much-needed change in wildlife health (Vicente et al., 2019).

We first advocate that research activities may be improved by considering questioning emerging from stakeholders. For example, about brucellosis, post-assessment of management measures is limited, and basically consisted in appreciating the temporal dynamics of the prevalence and the force of infection (Calenge et al. 2021, Lambert et al., 2022). The specific effects of each action have not been assessed, in terms of efficacy as well as unwanted effects, e.g. on ibex disturbance or population dynamics. The efficacy of each action could be assessed through modelling, using “what if” scenarios. The current situation of low prevalence also raises the question of whether brucellosis may fade out (with which probability or when), or alternatively whether the outbreak may start again and conduct to a similar situation as 2012 if management stops being efficient. Finally, the routes of transmission between ibex, chamois and cattle herds have still to be identified and deserve further attention.

We aimed to identify how to improve modelling in that context of decision-making. First, realistic models are hard to explain to non-scientific audience. However, the 2021 request to Anses showed that at least some stakeholders assimilated model results, as long as outputs relevant to them could be obtained and visualized. Complex models thus may not be a limit to science-decision interaction. Second, models should be flexible enough to test alternative scenarios and to be revised regularly, integrating new field data and epidemiological knowledge. In the case of brucellosis, decisions are taken on a yearly basis as population biology and management actions are highly seasonal. Thus, yearly cycles of modelling are relevant, provided the model is available at the time of reflection. The modelling process should thus become a continuous effort during the whole period of interest. Models also raise the question of which scenarios to consider: although all may be useful for a better understanding, scenarios that were considered as non-realistic or not acceptable were rejected, which limited model use. For example, a scenario of more than 50 captures per year

was considered unrealistic in 2021 (Anses, 2021). However, 135 animals were captured in 2022, thus model predictions were not comparable to field results. For the results to be assimilated by stakeholders, scenarios should be defined in concertation with them. Model should also consider the costs and benefits of management. Here, the total number of ibex culled and captured during the whole simulation period was estimated for various scenarios (Lambert et al., 2021) to provide elements to estimate the feasibility, the financial and organisational costs and the impact on population. Last, the ethical bases that served to identify the chosen scenarios should be clarified, so that a debate is possible on the conflict between values.

Research in social and political sciences could also be largely developed. In the case of brucellosis, although some preliminary studies have been conducted, the position of stakeholders, their interplay and possible avenues for changes have not been identified. Finally, philosophical values and ethical principles underlying management actions should also be identified, as well as their conflicts in such a complex system.

Finally, the main way to improve the use of research results by policy makers, field actors and the general public is to improve communication among them. Communicating model results on a complex system is challenging: for example, point estimates are more likely to be remembered than credible or confidence intervals, although such intervals are necessary to avoid the overinterpretation of point estimates. In this respect, the progressive acculturation to epidemiology by all actors is an essential issue, that implies a “de-appropriation” of knowledge by specialists. The accessibility of knowledge could also be increased and publicized, through French-speaking texts in the case of brucellosis. In particular, the outbreak monitoring is expected to generate transparent information on the epidemiological situation. However, this principle is limited by the necessary time to conduct investigations. Moreover, each structure may have its definition of what should remain confidential. A French-speaking OFB web page was updated in this purpose (<https://professionnels.ofb.fr/fr/article/point-foyer-brucellose-dans-massif-bargy>). A major challenge is to include uncertainty in communication and to avoid oversimplification. For example, models estimate probability of extinction, while policy makers ask for yes/no answer. The message that the future situation depends on stochastic, non-controllable events such as the place of abortion or the death of a few individuals is frustrating for some actors. As mentioned in the results, a key point for improvement is to define a place for concertation, and to organize a dialogue between scientists and stakeholders, as required for management cycle of wildlife diseases (Portier et al., 2019).

As a conclusion, brucellosis in ibex is a relevant model to learn how to manage diseases at the interface between wildlife, livestock and human health. The need for a long-term approach and for a permanent place of discussion between scientists, decision-makers and stakeholders are the main ways of improvement that may also serve for other host-pathogen systems.

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