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Abstract

This article presents a new model to manage the provision of healthy food despite incomplete information about exposure of natural resources to a persistent pollutant (chlordecone). This toxic molecule has contaminated both terrestrial and aquatic resources for several decades in the French West Indies. As a consequence, the threat of exposing humans to contaminated food jeopardizes local agricultural and livestock activities. We address the problem that breeders face: producing healthy food with incomplete information on the animals' contamination. We examine the compatibility of respecting health-production constraints with the timing of animal management. We consider the dual set of constraints that breeders face: (1) they must achieve a target contamination rate that complies with the regulation on the Maximum Residue Limits (MRL) and (2) they must comply with a production calendar that tells them at what age the animals are to be sold. We also discuss the economic and biotechnical consequences that changes in the MRL impose on meat production. We compute the time required to decontaminate the animals and analyse the cost for farmers to adapt to (i) the regulation in place and to (ii) the more stringent health-related targets that are expected in the future. Our results are sensitive to the choice of species cattle, goats, sheep and pigs), the rearing practices, the information setting and the initial contamination rate. This paper opens strategic windows for breeders to guarantee their economic sustainability and their ability to produce healthy meat despite the incomplete information on pollution at their disposal.

Keywords: Livestock, soil pollution, maximum residue limits for pesticides, safe meat production.

1 Introduction

During the last years, several events have challenged us to reconsider the interactions between agriculture, the environment and food production through the prism of health concerns. The need for an integrated approach to maintaining the health of ecosystems, animals and humans is now well-recognised. This is the case in regards to contagious diseases (avian flu, Ebola, COVID-19, etc.), food contamination (parasites, prions, persistent organic pollutants, heavy metals, etc.) and human practices (use of pesticides, industrial pollution, changes in animal feed and veterinary care practices, etc.).

Our aim is to identify the changes that are necessary in order to facilitate the production of healthy and sustainable food. This involves the designing of production systems that respect natural resources and are capable of providing a range of goods and services that can ensure the conditions for a healthy life. Both the preservation of ecosystems and the protection of animals' health are thus central to the effort of securing food supply and will help us to meet the Sustainable Development Goals [25].

Such health-related events have garnered much attention and interest in scientific literature [14, 21, 23]: Global Health, One health, Planetary Health, etc. This literature points towards the need to address health risks at the level of human-animal relationships. From the point of view of economic and social sciences, it raises questions regarding the sustainable management of the environment, agents' incentives and public policies [11].

In this paper, we analyse the difficulties faced by farmers aiming to produce meat that is safe for human consumption. We frame this analysis in the context of persistent soil pollution. Using the impact of chlordecone on the livestock systems in Guadeloupe as a case in point, this article examines the compatibility of respecting health-production constraints with the economic timing of animal management. It aims to identify the choice of species, as well as the breeding strategies, that can make this compatibility possible.

The French West Indies currently face soil pollution problems due to several decades of using the pesticide chlorinated polycyclic ketone (also called chlordecone or CLD) to control the black banana weevil (Cosmopolites sordidus). More than 25 % of the Utilised Agricultural Area is affected by this toxic pesticide, which contaminates both terrestrial and aquatic resources [3, 10, 8]. As a consequence, these terrestrial resources have been contaminated for the next 5 to 7 centuries [4]. The threat of exposing humans to contaminated food, caused by persistent environmental pollution, is a real public health problem [18, 20]. It is indeed the case that significant amounts of CLD can be found in the flesh, fat, organs, carcasses, milk and eggs of animals consumed by humans.

All the contaminated animal species are subject to surveillance and control programs. This form of monitoring consists of measurements such as the Maximum Residue Limit (MRL), which concerns the maximum concentration of the residue of a given pesticide that can be legally tolerated within animals.

Although measurements, carried out since 2008, have revealed the existence of high rates of contamination within animals [9], the intensity level of the contamination remains unknown. This is due to two main factors: firstly, not all of the forms of contamination are properly understood nor the level of contamination within any given animal is known. This lack of understanding is due to (i) incomplete knowledge on the metabolism of animals and (ii) the lack of information concerning soil contamination (insufficient number of soil analyses, inaccuracies in previous agricultural practices that may have led to soil contamination, mapping inaccuracies, etc.). Secondly, there are informal production and consumption systems that escape the scope of statistical identification and testing.

The ability to monitor the precise level of contamination within a living animal for all species, before slaughter, remains technically impossible for the moment. Farmers are therefore unable to be totally confident when marketing the meat that they produce. The fact that the information remains incomplete has forced some farmers to exit from the sector or even enter informal sectors of production where safe standards are not upheld.

As scientific and technical advances are made and the aspirations of society change, the threshold is set to increasingly low levels. Using the case of plant foods as an example, we see that the threshold, initially set at 50 $\mu g CLD \cdot kg^{-1}$ by the World Health Organisation, was lowered to 20 $\mu g CLD \cdot kg^{-1}$ in 2008.

We have observed a similar decrease in the threshold for animal products. The level was initially set at 100 $\mu g CLD \cdot kg^{-1}$ for pork, sheep and goat meat, and at 200 $\mu g CLD \cdot kg^{-1}$ for poultry (in accordance with regulation passed on February 23$^{\text{rd}}$, 2005). In France, the threshold was then lowered to 20 $\mu g \cdot kg^{-1}$ for all products in accordance with the inter-ministerial order of May 26$^{\text{th}}$, 2019. Such changes have provided reasons for consumers to distrust food produced locally [17]. In addition, these changes may also act as a disincentive for producers who would now be reluctant to invest in livestock activities given predicted demand expectations.

The case of CLD pollution has called the viability of breeding systems in the French West Indies into question. It is a problem that is faced by the majority of farmers, due to the way in which they practice rearing and grazing. Farmers seek to accumulate a positive income at the end of their activity knowing that the activity is subject to interdependent (health and economic) but timely distinct constraints: On the one hand, a biotechnical calendar linked to the process of contamination-decontamination of animals. On the other hand, an economic calendar linked to the management of animals in order to optimise the profit from sales.

Farmers are consequently impacted by a dual set of constraints:

1. A health-related constraint: they must achieve a target contamination rate that complies with the regulations (MRL) for each slaughtered animal.

2. An economic constraint: they must attempt to sell an animal at the optimal age in order to obtain a satisfactory price to guarantee their income.

The question we ask ourselves is the following: Is the time frame needed to produce healthy animals compatible with the economic constraints related to the commercialisation of the meat?

This question shares common features with [24] who analyse, for the African trade of mangoes, the trade-off between costs and benefits of the farmers to live from compliant products. Our paper brings two novelties: (i) Unlike most other papers that deal with safe plant and vegetable production, we analyse the case of livestock. (ii) Since animals (unlike plants) are subject to undergo a process of decontamination, this leads to a number of trade-offs that breeders have to face. These trade-offs do not exist in crops farming systems.

The remainder of the article is organized as follows: Section 2 is devoted to modelling the decontamination processes for animals. In section 3 we discuss the options available to a farmer when seeking to comply with the given health targets depending on the species being bred. In section 4 we evaluate the biotechnical decontamination strategies through the prism of the additional economic costs that farmers incur. Section 5 provides a conclusion.

2 Modelling contamination and decontamination of animals

In this section, we explain the basics of modelling the process of animal contamination and decontamination. Any animal that grazes a plot of land in which the soil is polluted by CLD will become contaminated. Its tissues, blood and organs will be saturated with increasing levels of CLD. This phenomenon of bioaccumulation has been proven to occur in all species. The only secure method to guarantee that an animal remains free from contamination is to stop it from being exposed to contaminated resources.

2.1 Bioaccumulation during the contamination phase

We must first make note of $\tau_{i,k}(t)$, which represents the level of contamination in the tissues of animal i, which is a member of the species k, and at a generic time t. In the case of an animal that grazes on contaminated soil, this contamination rate, $\tau_{i,k}$ is a function of the following factors: The contamination rate of the animal at its arrival on the farm, $\tau_{i,k}(0)$; the soil pollution rate, σ[1]; the duration of the contamination phase, C; its species k.

This gives the following mathematical relationship:

$$\tau_{i,k}(t) = f(\tau_{i,k}(0), \sigma, C, k) \ . \tag{1}$$

All the animals belonging to the same species which are grazing on the same plot will tend, after a certain time, towards having the same level of contamination, apart from some minor inter-individual variations. These inter-individual variations will not be considered in this paper and, in order to simplify the mathematical notations, the index i corresponding to each individual will not appear henceforth ($\bar{\tau}_k$).

Excessive contamination and the need for decontamination

When the duration of exposure, as well as the contamination rate of the soil, are sufficiently high, the contamination rate of the animal grazing on it becomes excessive and its meat is no longer considered fit for human consumption. To be precise, if the level of contamination present in the animal exceeds the authorized MRL threshold, its meat cannot be marketed through the formal sector. The breeder must then decontaminate each animal to ensure that the level of contamination in the animal's tissue is below the MRL before the animal is slaughtered.

During the decontamination phase the animal is no longer exposed to CLD. This forces the breeders to modify their practices. Such changes are costly and include stabling the animals and providing uncontaminated pasture.

Let A_{0k} denote the age at which an animal of the species k entered the farm. Likewise, A_{Dk} represents the age of the animal when the breeder begins the decontamination phase. Let A_{Tk} denote the age of the animal at the moment when it is due to be slaughtered.

Figure 1 provides a graphical representation of the evolution of the contamination level within the animal during these two phases.

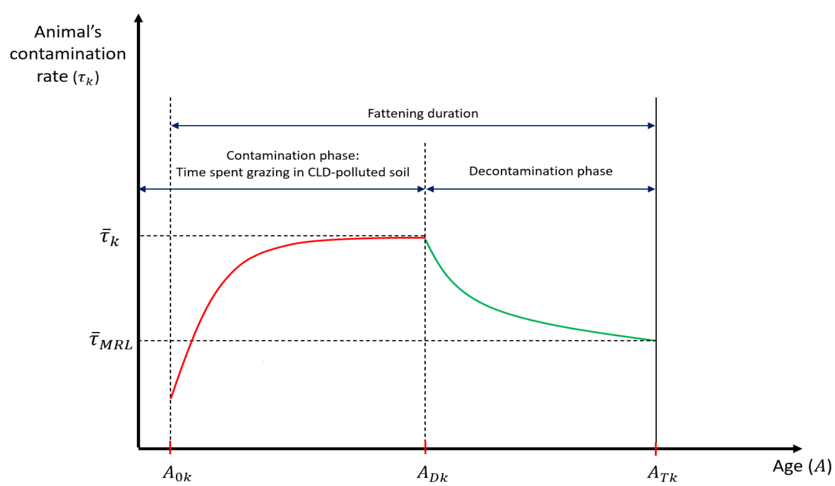

Fig.1 The evolution of the chlordecone level in the animal during the contamination and decontamination phases

The period between 0 and A_{Dk} represents the duration of the contamination phase (i.e. the animal may start to contaminate before arriving at the fattener's farm) and $A_{Tk} - A_{Dk}$, that of the decontamination phase. Note that the entering age is not necessarily zero (we are dealing with fatteners in this study) and the contamination rate of the animal at the age of arrival (A_{0k}) is not necessarily null. Note also that the evolution of the animal's contamination rate is non-linear with a saturation point: Whatever the initial contamination rate of the animal, its contamination level will naturally converge towards an asymptotic contamination level, further denoted $\bar{\tau}_k$.

2.2 The half-life and the contamination rate during the decontamination phase

Every breeder is obliged by law to market meat that is fit for human consumption. The contamination rate displays a non-linear rate of evolution during the decontamination phase:

$$\tau_T = \tau_D \cdot e^{-\lambda_k \cdot D_k} \tag{2}$$

where τ_T is the final level of contamination at the date of slaughter and τ_D the contamination rate when the animal begins the decontamination phase[2]. The length of the decontamination phase, D_k, is $D_k = A_{Tk} - A_{Dk}$, where A_{Tk} and A_{Dk} are not known and have yet to be determined.

In Equation (2), the value of λ_k can be deduced from the half-life ($\hat{t}_k$). This half-life is the number of days of decontamination (i.e. non-exposure) necessary for the contamination rate of an animal of a species k to drop to a level twice as low as it was at the beginning. This half-life for CLD decontamination was determined for the species that are analysed in this paper by [15] and [12].

If we replace D_k in Equation (2) by the half-life ($\hat{t}_k$) and we consider that the final rate will be half of the initial rate, we obtain: $\frac{\tau_D}{2} = \tau_D \cdot e^{-\lambda_k \hat{t}_k}$.

After algebraic manipulations, we can deduct the value of λ_k from that of the half-life $\hat{t}_k$:

$$\lambda_k = \frac{\ln 2}{\hat{t}_k} \; . \tag{3}$$

2.3 The length of the decontamination phase

Any animal whose contamination rate exceeds the limit threshold (here $\bar{\tau}_{MRL}$) must undergo a decontamination phase. We want to know the length of the decontamination phase to be observed so that, whatever the contamination rate at the beginning, it becomes at most equal to $\bar{\tau}_{MRL}$ at the end of the decontamination phase[3].

This calculation is made by using the expression (2). After isolating the exponential and making a log-log transformation we obtain: $\ln(\frac{\tau_D}{\bar{\tau}_{MRL}}) = \lambda_k \cdot D_k$.

If λ_k is replaced by the value obtained in Equation (3), the decontamination length (D_k) can then be expressed as follows:

$$D_k = \frac{\hat{t}_k}{\ln 2} \cdot \ln(\frac{\tau_D}{\bar{\tau}_{MRL}}). \tag{4}$$

The formula presented above is applicable regardless of the age of the animal when it enters the farm or the species to which it belongs. It shows that, for a starting rate equal to τ_D, the decontamination phase must last at least $\frac{\hat{t}_k}{\ln 2} \cdot \ln(\frac{\tau_D}{\bar{\tau}_{LMR}})$ days, if the maximum contamination rate admissible at the date of slaughter is equal to, or lower than, $\bar{\tau}_{MRL}$.

In order to do this, the farmer must begin to decontaminate an animal of a species k at an age denoted by A_{Dk}. The value of A_{Dk} still needs to be determined.

2.4 Uncertainty and decontamination: How can we determine the beginning of the decontamination phase?

We have previously showed that the length of the decontamination phase is a function of the contamination rate of the animal just before the decontamination phase begins. The contamination rate of the animal is, in turn, a function of the soil contamination rate. And the rate of soil contamination is often unknown. Indeed, not all farmers have all the necessary information regarding the level of soil contamination within their plot. Most importantly, the level of contamination within an animal, at any given moment, remains unknown and impossible to observe. This leads to an inability to determine the level of contamination within the animal before it is slaughtered. How should we therefore determine the date at which the decontamination process of the animal must start?

The decontamination deadline in the context of incomplete information

Three solutions are available to the farmer. They depend on the information available regarding the following factors:

1. The rate of contamination towards which the animals in the farmer's plot will naturally tend to converge (we denote this rate the 'asymptotic rate').
2. The rate of contamination of the soil in the farmer's plot.

As seen in Figure 1, the rate of contamination within the animal converges asymptotically following a logarithmic-exponential law. The speed of convergence plays an important role here: If the time it takes for the rate of contamination to stabilize is shorter than the length of the contamination phase (i.e. if the speed of convergence is high), then the time when the decontamination begins can simply be inferred from the asymptotic contamination rate. We do not need take measurements of the rate of contamination within the animal at any given moment as we can instead deduce it by using the asymptotic rate.

The first case: The asymptotic contamination rate ($\bar{\tau}_k$) towards which the animals of a given plot converge can be used as an input for the initial rate of contamination in Equation (4).

In this scenario, the rate of soil contamination may be unknown, but the asymptotic rate of the bioaccumulation that occurs within animals provides a sufficient level of information on which farmers can establish a strategy. They operate as if they were in a context of having complete information.

In order to determine the duration of the decontamination phase as a function of this asymptotic rate, we replace τ_D in Equation (4) by $\bar{\tau}_k$. This gives the following expression:

$$\bar{D}_k = \frac{\hat{t}_k}{\ln 2} \cdot \ln(\frac{\bar{\tau}_k}{\bar{\tau}_{MRL}}) \ , \tag{5}$$

where $\bar{D}_k$ is the length of the decontamination period that corresponds to this asymptotic rate.

The second case: The farmer does not know the level of contamination within his/her animals but does know the level of soil contamination in the plot. If the exposure time and the rate of soil contamination are known, all the breeder needs is to estimate the mathematical function which explains the evolution of the contamination rate as a function of these two arguments. Using Equation (1) the contamination rate of the animal can be estimated $\hat{\tau_k}$ for a given instant t. The length of the resulting estimated decontamination phase is:

$$\hat{D}_k = \frac{\hat{t}_k}{\ln 2} \cdot \ln(\frac{\hat{\tau}_k(t)}{\bar{\tau}_{MRL}}) \ . \tag{6}$$

At this point it is important to note that experiments concerning the contamination of animals have been undertaken, notably in the case of the ovine species [12]. That being said, we are still far from being able to provide parametric functions that can describe the evolution of the contamination rate during the course of the contamination phase.

In this scenario, if farmers were able to know the level of contamination of the soil, as well as the evolution law of the rate of contamination in the animal, they would also be able to determine the rate of contamination with sufficient precision, i.e. as if they had complete information.

Third case: Without any information regarding the rate of contamination within either the animals or the soil, it becomes risky to favour any precise rate of reference such as an average rate over a large number of farmers in the territory. Indeed, using such a ‘representative rate of contamination’ as a means to comply with the MRL would result in a decontamination period that would be too short for a large share of the population (e.g. half of the population if the chosen representative rate was, say, the median). Farmers should rather seek a solution that works in all cases. This implies reasoning in a scenario that consists in systematically assimilating animals to the worst observed case. Let us use τ_k^{WCS} to denote the highest rate of contamination ever recorded for a given species k. One can replace $\bar{\tau}_k$ by $\bar{\tau}_k^{WCS}$ in Equation (4) in order to determine the length of the decontamination period (D_k^{WCS}) that will lead to compliance with the MRL in the worst-case scenario:

$$D_k^{WCS} = \frac{\hat{t}_k}{\ln 2} \cdot \ln(\frac{\tau_k^{\bar{WCS}}}{\tau_{\bar{MRL}}}) \; . \tag{7}$$

Determination of the age when decontamination begins

Equations (5), (6) and (7) provide the length of the decontamination phase in accordance with the information that is available to the farmer. That said, these expressions still do not inform the breeder about the age at which the animal should start to undergo the decontamination process nor the age at which it should be slaughtered.

Regarding the latter, farmers must attain certain objectives. These objectives are expressed in terms of the age and weight of the animal and are related to cost-benefit trade-offs associated with the breeding process (e.g. the daily cost of feeding and fattening the animal with respect to the daily weight gain).

In this paper, the age at which the animal will be slaughtered is not called into question. Instead, it is taken as a given. We know that the meat industry requires that the animal be slaughtered at a fixed age (A_{Tk}). We also know the length of the decontamination phase. As seen above, this length will depend on the scenario the farmer finds him/herself in. To determine the age limit at which the decontamination process must be started (A_{Dk}), a backwards time calculation is required:

$$A_{Dk} = A_{Tk} - D_k \; , \tag{8}$$

where A_{Tk} is known precisely and D_k is to be replaced by $\bar{D}_k$, $\hat{D}_k$ or D_k^{WCS} depending on the case.

3 Is the health target achievable?

In this section, we seek to illustrate breeding strategies for which the biotechnical timetable for decontamination of the animal is compatible with the economic schedule for marketing the meat in the French West Indies[4].

3.1 Data presentation

The available data are patchy and not complete for all species. For example, in Guadeloupe, as noted in Section 2, the rate of soil contamination σ, as well as the initial rate of contamination of the animal on its arrival at the farm ($\tau_k(0)$), are not necessarily known. The presence of these unknown variables illustrates the fact that situations exist where the farmers can own a contaminated animal without knowing the initial level of contamination and yet they will be obliged to bear all of the costs of decontaminating the animal during the period leading up until its slaughter. This scenario is close to the observable reality where farmers of any status (i.e. breeders, fatteners, breeder-fatteners) are only able to discover the level of contamination within their animals at the time of their slaughter.

Various data (e.g. technical, economic, pharmacokinetic, as well as data on animal contamination rates) have been collected for each of the species. The data at our disposal concern Guadeloupe island.

The technical and economic data have been collected through the use of surveys addressed to farmers that were designed to help us understand the current management of animals on the farm [16]. These data include the age at which the animal enters the farm, typically after weaning (A_{0k}); the slaughtering deadline for marketing the meat (A_{Tk}); and the time required to fatten the animal ($A_{Tk} - A_{0k}$). Pharmacokinetic data on the bioaccumulation of CLD in animals are available in the scientific literature thanks to laboratory experiments [15].

Data regarding animal contamination have been collected by State departments (i.e. the French Ministry of Agriculture and the French Ministry of the Economy and Finance) through a process of monitoring and by implementing control plans [9]. These plans have a threefold objective:

1. To avoid the selling of meat that is not compliant with health and safety regulations.

2. To improve knowledge regarding the use of phytosanitary products.

3. To define the levels of contamination of primary production (plant and animal), foodstuffs of animal origin and animal feed.

On the one hand, monitoring plans serve to assess the overall exposure of consumers to a particular contamination risk (in this case the risk of CLD contamination). These measures have been established on the basis of random sampling and without predefined targeting. On the other hand, the control plans target a range of foodstuffs that present a contamination risk that depends mainly on the type of foodstuff and its geographical origin. They are thus part of a wider effort to monitor and evaluate the practices of producers.

Whenever the contamination rates are missing, the missing data has been completed using experimental data. When analysing the rate of contamination observed in the case of cattle and pigs, we refer to data from the monitoring and control plans [9]. The data on goats and sheep are obtained from experiments that involve the deliberate contamination of animals under controlled laboratory conditions [12, 15].

Using these data, it is possible to derive new statistics on which one can base the analysis of the compatibility of both decontamination and economic schedules. For each level of contamination that has been observed (τ_k^{WCS}), the maximum decontamination time (D_k^{WCS}) is calculated according to Equation (7).

For each species, it is also possible to calculate a theoretical maximum contamination rate (τ_k^{MAX}), that is compatible with both the health requirements and the economic constraints of selling the meat. Such theoretical maximum can be obtained using the function defined in Equation (4) and setting D_k equal to $A_{Tk} - A_{0k}$:

$$\tau_k^{MAX} = \bar{\tau}_{MRL} \cdot e^{\frac{ln2}{t_k} \cdot (A_{Tk} - A_{0k})} \ . \tag{9}$$

Since the decontamination duration used in Equation (9) is the whole fattening duration ($A_{Tk} - A_{0k}$), τ_k^{MAX} gives the highest initial contamination that is compatible with achieving $\tau_{M\bar{R}L}$ at the end of the fattening period. In other words, if the initial contamination rate upon arrival is beyond τ_k^{MAX} the farmer will not have enough time to decontaminate the animal before A_{Tk}.

Note that since 2019 the legal standard (i.e. MRL) has been made stricter in France. The accepted threshold has decreased from 100 $\mu gCLD \cdot kg^{-1}$ to 20 $\mu gCLD \cdot kg^{-1}$ for the four species that are considered in this paper (cattle, goats, sheep and pigs). Since the value of the maximum theoretical contamination rate is linked to the legal standard, as the legal threshold level changes so does the theoretical maximum. We have thus determined τ_k^{MAX} for all four species and for the former and the current level of the MRL.

Note also that the expectations imposed by society may change. Many actors have expressed their fears about the CLD risk. Some have proposed the creation of a "zero chlordecone" label[5] For this reason we have analysed the consequences of a close-to-zero CLD standard, as well.

To summarize, for each considered species, we seek to know what is the maximum initial level of contamination (τ_k^{MAX}) that guarantees that, after decontamination, the legal standard ($\tau_{M\bar{R}L}$) can be met at the slaughter age (A_{Tk}). We reason under different standards: the current standard, which came into force in 2019 (MRL 20 =20 $\mu g \cdot kg^{-1}$). The zero CLD standard[6] (MRL $0^+ \cong 0 \mu g \cdot kg^{-1}$). In addition, from a retrospective perspective, we consider the standard that prevailed until 2019 (MRL 100 =100 $\mu g \cdot kg^{-1}$). The question we seek to answer is this: Following the changes to the MRL, are the biotechnical constraints and the economic constraints of animal management compatible with one another?

All the relevant information to answer this question can be found in Table 1 below:

Table 1 Technical, biological and pharmacokinetic data

	Cattle	Goat	Sheep	Pig
Half life*** (days)	45	20	23	55
Age of the animal on arrival in farm* (months)	8	10	3,5	9
Fattening duration* (months)	22	6	5,5	3
Slaughter age* (months)	30	16	9	12
Highest contamination rate observed in Guadeloupe (2018) (µg.kg-1)	650**	670****	160***	1650**
Theoretical maximum contamination rate MRL100 * (µg.kg-1)	> 520160 ǂ	51200	14440	311
Theoretical maximum contamination rate MRL 20 *	520160 ǂ	10240	2888	62
Theoretical maximum contamination rate MRL0+ *	13004	256	72	2
Maximum decontamination time compatible with the MRL100 * for	]120-150[#	]30 - 60[#	< 30	]210-240[#
Maximum decontamination time compatible with the MRL0+ * for the observed contamination rate (days)	]450 - 480[#	]180 - 210[#	]180 - 210[#	> 365

ǂ By using the half-life function we obtain a level that is significantly beyond 10^{-6} µg per kg. Since it is technically impossible to find such high concentration rents, we have simply written: > 520160 which is the level that was found for MRL 20.

In the last three lines, decontamination intervals correspond to inter-animal variations.

The first three rows in Table 1 provide the reference background for all four species. In this paper we deal with farmers (fatteners) who typically buy male animals from breeders for the purpose of rearing them, after the breeders have finished the weaning process. The arrival age of the animals to the farm (first row in Table 1) coincides with current practices in the French West Indies [16]. The slaughter age (second row of Table 1) is given by [16]. The fattening duration (third row) is simply computed as the difference between the slaughter age and the age of the animal on arrival. This fattening duration coincides with the maximum theoretical decontamination length.

The second part of Table 1 (rows 4 to 7) is related to various pharmacokinetic data. On the fourth row, we show the half-life for each species. This half-life, expressed in days, gives the time necessary to reduce the current level of contamination in the animal's tissues to half. Note that this half-life is a theoretical function obtained from experimental data. The half-lives are different for every species. As mentioned above, there exist also some minor inter-individual variabilities within every species, i.e. some individuals eliminate the CLD molecule from their bodies faster than others. These minor inter-individual variations are not taken into account in this paper.[7]

In rows 5 to 7 we compute the maximum theoretical initial contamination rate (τ_k^{MAX}) by using Equation (9) for each species (i.e. for each half-life) and for each different legal threshold (i.e. MRL 100, MRL 20, MRL 0^+). Since we are looking at a theoretical maximum, the decontamination length used to feed Equation (9) is the maximum decontamination length possible, i.e. the fattening duration.

The results can be compared with the highest contamination rate observed for each species (row 8). The values displayed in row 8 can be assimilated to τ_k^{WCS}.

At this point it is important to compare the results in rows 5-7 (τ_k^{MAX}) with those in row 8 (τ_k^{WCS}). Whenever $\tau_k^{MAX} > \tau_k^{WCS}$ it is feasible to decontaminate the animal within the fattening duration and vice versa. The results show that, for the current legal threshold (MRL 20), all the species analysed except pigs can be decontaminated. For a more detailed analysis for each species see Section 3.2.

An equivalent way to determine whether reaching the target MRL is feasible (for any given species, for any given initial rate of contamination and for any given legal threshold) is to obtain the minimum necessary decontamination length and then compare it with the fattening duration. We have used Equation (7) to compute, in the last three rows of Table 1, the time length of the decontamination phase required for an animal whose initial contamination level is τ_k^{WCS} (i.e. the contamination level displayed in row 8).

Whenever this length is greater than the fattening duration, it is not possible to decontaminate the animal in time. In other words, the health and the economic requirements enter in contradiction.

3.2 Health-related target and choice of species: A two-pronged issue

In light of the above data, we seek to understand to what extent the "economic calendar" (i.e. the time that must be dedicated to rearing the animal until the optimal slaughtering age is reached) is compatible with the "decontamination calendar" of the animal (otherwise known as the decontamination length). The question to answer is: Is the health target reachable or not? Or in other words, does the level of contamination within the animal leave the possibility of undertaking the decontamination process on time?

If the decontamination length is shorter than the fattening duration, both calendars are compatible and the health target is deemed reachable. Else, if the decontamination length prescribed is longer than the fattening duration, then the health-related targets and the economic targets enter in contradiction with one another and the health target is deemed not reachable. See Table 2 below:

Table 2 The attainability of the health target

	Cattle	Goat	Sheep	Pig
Health target LMR100	Reached	Reached	Reached	Unreachable
Health target LMR20	Reached	Reached	Reached	Unreachable
Health target LMR0+	Reached	Undetermined response	Not reached	Unreachable

The results obtained in Table 2 are explained by the interplay of three key factors: (i) the speed at which animals become contaminated, (ii) the speed at which they can be decontaminated, and (iii) the fattening duration.

3.2.1 The ideal case: cattle

Although cattle have a larger half-life than goats and sheep, and despite the fact that the contamination levels observed in some cows are very high, cows have a much longer fattening duration which allows them to be decontaminated in all cases.

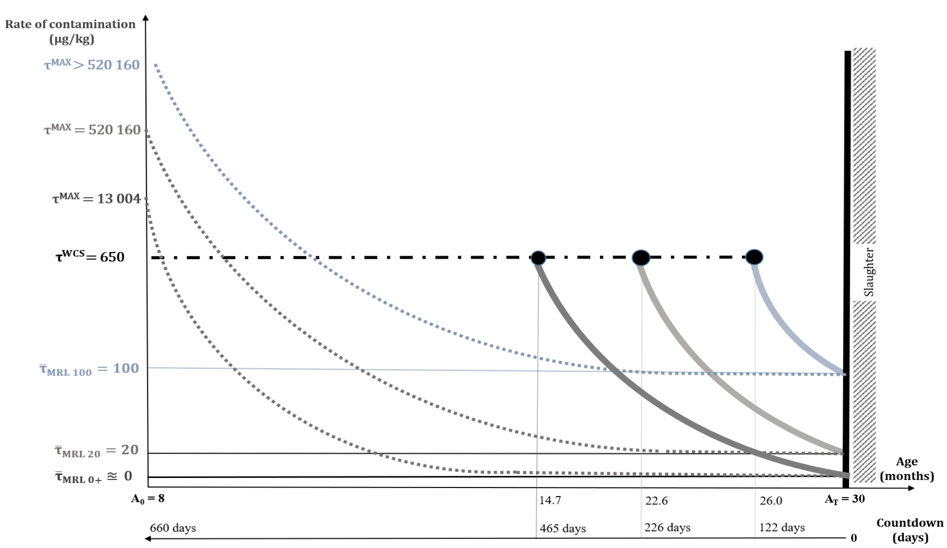

Fig. 2 Cattle decontamination is feasible for all of the situations analysed

The value obtained for τ_{cattle}^{MAX} is very high: 13 004 $\mu g \cdot kg^{-1}$ for MRL 0^+ and 520 160 $\mu g \cdot kg^{-1}$ for MRL 20. Such levels are never reached in reality.

The required decontamination time is always shorter than the maximum fattening time for all the scenarios analysed.

For the case of the outdated MRL 100, the maximum period required for decontamination phase was 122 days. Whereas for the current MRL 20, 226 days will be needed to decontaminate. Finally, to reach the MRL 0^+, 465 days of decontamination will be required to reach the target if the initial contamination level is equal to 650 $\mu g \cdot kg^{-1}$.

From a purely health-based point of view, it is feasible to envisage a transition to the use of a "zero chlordecone" label in the cattle-production industry given the current state of rearing practices. The health target remains achievable for cattle farmers and is also fully compatible with the economic schedule related to the management of animals. As a consequence, the bovine species has great strategic interest both currently and in the case of a possible tightening of regulation in the future.

3.2.2 The worst case: pigs

In the case of pigs, the ability to comply with the health-related targets will always be compromised regardless of the MRL threshold considered. This can be explained by the fact that pigs have a relatively long half-life (almost two months) and a short fattening period.

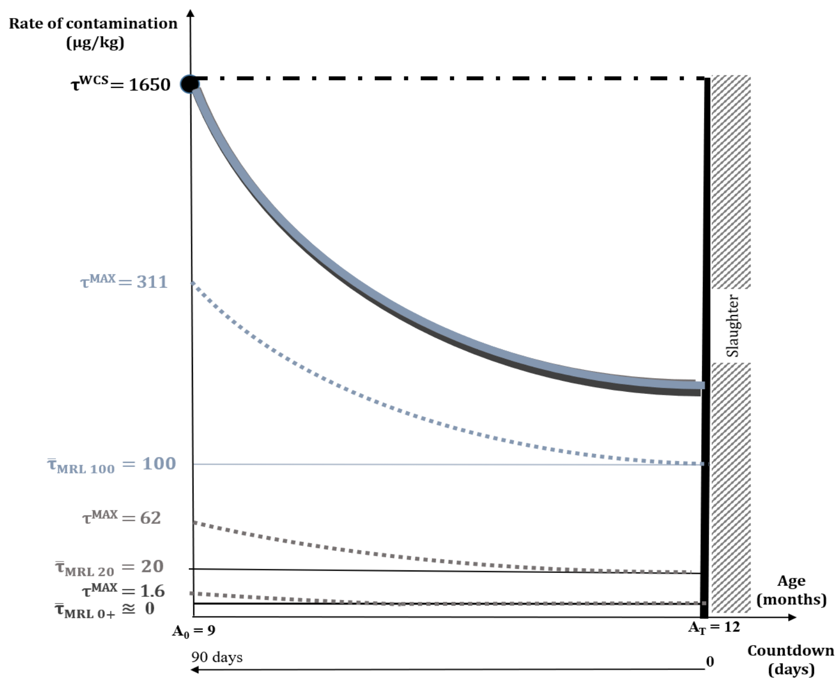

Fig. 3 Pig decontamination is not feasible for any of the situations analysed

If we consider the worst-case scenario where the initial rate of contamination is 1650 $\mu g \cdot kg^{-1}$, and where the former MRL 100 is followed, it would be necessary to devote 222 days to decontaminating the animals (i.e. 7.3 months). More than double the standard fattening duration (3 months).

Even if the maximum rate of contamination that has been observed in Guadeloupe (τ^{WCS}_{pigs} = 1 650 $\mu g \cdot kg^{-1}$) is -according to experts- abnormally high, any animal with an initial contamination level above the very plausible 311 $\mu g \cdot kg^{-1}$ could not have finished its required decontamination process before the slaughter age.

For the current and more stringent MRL 20 limit, the maximum theoretical contamination level compatible with the achievability of the health target is 62 $\mu g \cdot kg^{-1}$ which is much lower than what we observe in reality.

If one aims at the MRL 0^+ target, then the maximum initial contamination rate that is compatible with it is 1.6 $\mu g \cdot kg^{-1}$. This level is several hundred times lower than the typical contamination levels observed. For the highest observed contamination levels, even one whole year devoted to decontamination would not suffice.

These decontamination calendars are therefore incompatible with the economic calendar. In view of these findings, rearing the pig species with the observed contamination levels and the new health target is infeasible. Only animals reared since birth in non-contaminated plots of land will respect the health targets imposed.

3.2.3 The intermediate case: goats and sheep

Based on the maximum rates of contamination that have been observed (τ^{WCS}_{goats}, τ^{WCS}_{sheep}), goat and sheep farmers will find the current situation (MRL 20) satisfactory as far as health issues are concerned.

According to [15], the half-life for sheep is 23 days, whereas it is comprised between 9 and 20 days for goats. We have considered the most unfavourable configuration by retaining the longest half-life (i.e. 20 days for goats and 23 days for sheep) and the highest contamination rate found in the literature.

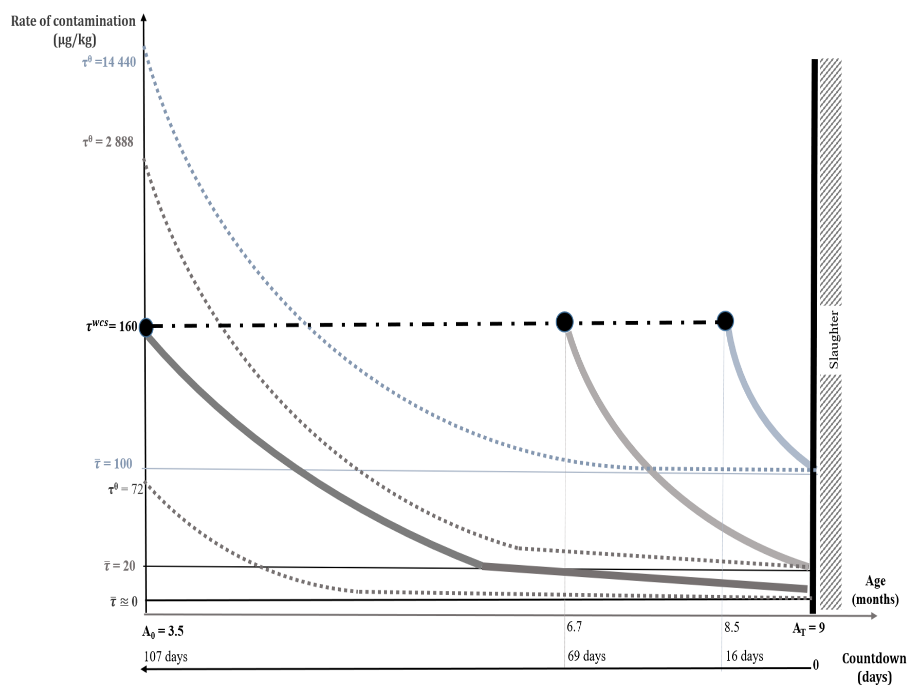

Fig. 4 Sheep decontamination is feasible for MRL 20 but not for MRL 0^+

For sheep, a maximum of 69 days of decontamination will be needed in order to reach the MRL 20 threshold. Sheep do not offer the possibility of being able to comply with a further tightening of health regulations (MRL 0^+). Indeed, in light of the time period required for fattening the animal, the time period needed to decontaminate the animal becomes too long (6.3 months), whereas the fattening period lasts only 5.5 months.

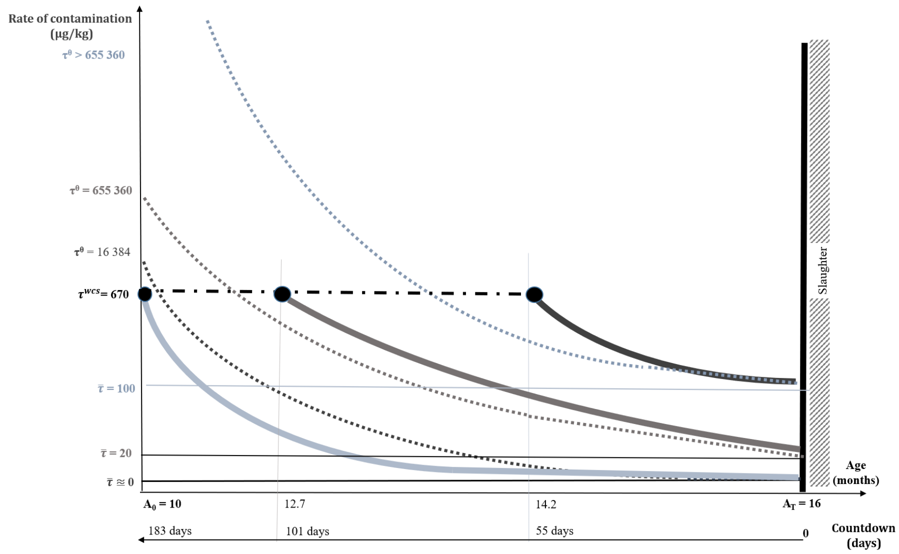

Fig.5 Goat decontamination is feasible for all cases of figure

Goats have a similar half-life, but much higher contaminations rates have been observed. For the highest contamination levels observed (670 $\mu g \cdot kg^{-1}$) the MRL 20 threshold can be reached after 101 days of decontamination.

The same is true for the more stringent MRL 0^+. For goats, unlike with sheep, the more stringent MRL0^+ is attainable for the worst-case scenario after 183 days of decontamination.

The fact that the MRL 0^+ is attainable for goats and not for sheep despite the goats' higher contamination rates is explained by the much longer rearing duration (10 months for goats as opposed to only 5.5 months for sheep). Our results are aligned with those of [19] that have emphasized the comparative advantages of working with the goat species. As we will see later, the conclusions obtained for this MRL 0^+ change when the economic costs of decontamination are taken into account.

To sum up the conclusions reached by analysing the results in Table 1, the only species that cannot ensure that farmers will be able to comply with the new and more stringent health-related standards (i.e. MRL 20) is the pig species. This has been proven by analysis of both the biotechnical and economic calendars. In terms of the three other species (cattle, goat, and sheep), the health target is achievable within the current health standards. The transition to the stricter MRL 0^+ is feasible for cattle, whereas such more stringent levels may not be achievable for sheep (not enough time to decontaminate) or goats (too costly to decontaminate).

As long as the regulatory status quo (i.e. MRL 20) does not change, goat and sheep remain attractive prospects.

4 Which decisions must farmers take in relation to economic concerns?

By comparing the above-mentioned data with the costs incurred by undertaking the process of decontamination, the breeders are able to better define their decision rule. This insight makes it possible to assess the profitability of livestock production from a cost-benefit perspective. We only consider cattle, sheep and goat species here, because the health-related target can be reached. The pig species has been excluded from the analysis, since the health target is incompatible with the economic calendar.

4.1 Economic data

The sources of the data that has been collected include scientific literature [1, 2] and the gray literature pertaining to the agricultural profession [13, 16, 22]. They concern professional livestock farms.

In order to decontaminate an animal, it must not longer face exposure to the CLD molecule. This can be achieved through the use of two strategies: the animal can be transferred to an uncontaminated plot to forage, or it can be placed in a stall with feed supplements. The observation of local rearing practices in the French West Indies shows the spread of important backyard animal productions. Farms are generally small (they only contain about ten animals within the pasture). The farmers do not generally invest in buildings dedicated to the fattening of animals that are more adapted for use on big farms.

Four sets of costs have been calculated. The calculations have been made for the MRL 100, the MRL 20 and the MRL 0^+. More stringent health targets imply longer decontamination phases. Decontamination is costly. Therefore, rearing costs will be greatly impacted by the choice of the target.

Generally speaking, the monthly rearing costs per animal are a function of the following factors: the species, the type of practice (pasture grazing, stabling), the sex of the animal and the animal's age (some costs arise at particular ages or times, such as the contribution to legalize a newly acquired animal). These costs can be summarised in the following expression:

$$C_{i,k,t} = f(k, \theta, s, A) \ , \tag{10}$$

where i denotes the individual; k denotes the species; t denotes time; θ denotes the type of practice which is influenced by whether the animal is currently undergoing decontamination or not; s denotes its sex; and A denotes the animal's age.

In Table 3, all costs are shown for the three retained species. For all the species, the total monthly rearing costs are, first and foremost, determined by the type of practice (grazing vs. decontamination). Decontamination necessarily involves buying food and supplements which greatly increase the monthly cost.

All costs in this paper have been computed for males[8] of all species. The age variable triggers a variety of costs. These include the expenses dedicated to animal maintenance (i.e. feed and veterinary care), various fees and materials that must be purchased in order to identify animals (e.g. tags) and fixed costs related to the installation of small equipment to house the animals.

In Table 3 (rows 3 to 6) we account for all the fixed and variables costs, both related and non-related to decontamination. To determine the total cost paid for rearing an animal, all one needs to know is the length of the decontamination phase which is linked to the animal's initial rate of contamination as given by Equation (3).

To simplify the reader's task, all the fixed and variable costs have been aggregated (rows 7 to 9) to obtain a monthly average. This average monthly cost includes all the costs related to decontamination. The decontamination costs have been smoothed across the total time spent by the animal in the farm and not just during the decontamination phase.

The results show that, in all cases, the average monthly cost increases (e.g. from 69.66 EUR$\cdot$ month^{-1} to 80.57 EUR$\cdot$ month^{-1} for cattle) when the health target becomes more stringent. Clearly, more stringent health targets imply a longer decontamination phase, which will translate in an increase in the total rearing costs.

It is also worth noting that all the cost calculations in rows 7 to 9 have been made for an initial contamination level equal to that of the worst-case scenario (i.e. the highest observed contamination level) presented in Table 1. In other words, the decontamination costs retrieved correspond to the durations obtained in Table 1 and represent an upper bound. If a farmer has some more precise knowledge of the asymptotic rate of contamination of the animals grazing in the plot, then more accurate (i.e. lower) cost estimates can be made with the help of the information available in rows 3 to 6.

Table 3 The calculation of the economic costs and benefits for rearing practices in a chlordecone-contaminated area

	Cattle	Goat	Sheep
Duration of fattening (month)	22	6	5,5
Asymptotic contamination rate of reference (µg/kg)	650	670	160
Maximum decontamination time compatible with MRL20 for the observed contamination rate (month)	]7 - 8[	]3 - 4[	]2 - 3[
Maximum decontamination time compatible with the MRL0+ for the observed contamination rate (month)	]15 - 16[	]6 - 7[	]6 - 7[
Monthly gross product (euro/ animal)*	153,86	21,93	42,86
Monthly cumulative theoretical costs related to decontamination (euro/ animal)*	84,91	26,4	38,37
Monthly cumulative costs related to decontamination MRL20 (euro/ animal)*	[64,46 - 65,82]	[16,89 - 18,25]	[28,17 - 30,72]
Monthly cumulative costs related to decontamination MRL0+ (euro/ animal)*	[75,37 - 76,73]	[20,97 - 22,33]	-
Profit MRL20 (euro/ animal)*	[88,04 - 89,40]	[3,68 - 5,04]	[12,14 - 14,69]
Profit MRL0+ (euro/ animal)*	[77,13 - 78,49]	[-0,40 - 0,96]	-

The gross product per animal has been computed. This gross product includes the various subsidies received as well as the turnover expressed in EUR $\cdot kg^{-1}$ of carcass. The result is obtained after dividing by the total fattening duration to obtain its monthly equivalent (row 10 of Table 3).

Once the monthly gross product is known, it is straightforward to obtain the monthly profit (rows 11-13) as the difference between the gross product and the average cost that applies in each case. The total profit can be retrieved by simply multiplying by the total fattening duration.

4.2 The economic targets and the choice of species

The previous data permit us to discuss and analyse the economic conditions that affect breeding activity depending on the different species concerned. Considering the economic objectives, two configurations are identified according to the choice of species.

1. The ideal case of cattle

The comparison between costs and revenues related to the implementation of decontamination strategies reveals that the activity is economically profitable whatever the value of the MRL. The farmer is certain to make a profit in all cases of figure. The profit ranges from 72.89 EUR $\cdot$ animal$^{-1}\cdot$ month^{-1} (for MRL 0^+) to 88.29 EUR $\cdot$ animal$^{-1}\cdot$ month^{-1} (for MRL 100).

More stringent health objectives can be envisaged, even if they are more costly: Shifting from MRL 100 to MRL 20 increases the total cost (per animal) by 101.86 EUR (i.e. the difference in costs (88.29 - 83.66) times the fattening duration). Whereas shifting from MRL 20 to MRL 0^+ implies an increase in the total cost that is equal to 237.04 EUR.

2. The ambiguous case of goat and sheep

As far as goats are concerned, the activity remains profitable when operating within the limit of the MRL 20. It generates a net income of 6.67 EUR$\cdot$ month^{-1} for MRL 100 and 4.63 EUR$\cdot$ month^{-1} for MRL 20. The total cost (for the whole fattening duration) for shifting from MRL 100 to MRL 20 is equal to 20.40 EUR$\cdot$ animal^{-1}. Likewise, the cost for shifting from MRL 20 to MRL 0^+ is 47.25 EUR. More importantly, the profit becomes negative (-0.12 EUR$\cdot$ month^{-1}). In other words, although MRL 0^+ is an achievable target from the health perspective, it is not profitable from the economic perspective.

In regards to sheep fattening, the activity is profitable when operating within the limits of the MRL 20 (13.69 EUR$\cdot$ month^{-1}). Shifting from MRL 100 to MRL 20 has increased the total rearing cost as much as 27.5 EUR$\cdot$ animal^{-1}. Should the farmer be obliged to follow the MRL 0^+, the idea of developing a profitable sheep farm is not viable due to the impossibility to decontaminate within the fattening duration.

When we compare the differences between the cost structures that must be implemented when following the MRL 20, and the MRL 0^+, we can see that stricter regulatory standards always encompass lower profit margins.

The results obtained underline the necessity for farmers to carefully adjust the composition of their livestock systems given the sensitivity of the species to CLD contamination and decontamination and the costs generated by the latter (Table 3).

With the current MRL 20 threshold, running goat and sheep farms generates a low profit for farmers. Even more so for farmers with highly polluted pastures. This is the case even if goats and sheep can be decontaminated more quickly than other species.

Table 4 Economic profitability for different health targets

	Cattle	Goat	Sheep
Economic target MRL20	Reached	Reached	Reached
Economic target MRL0+	Reached	Not reached	-

A further tightening of the MRL will have even greater repercussions making goat and sheep fattening farmers non profitable.

The biotechnical advantage obtained by raising goats and sheep due to their faster decontamination periods is lost if more stringent targets are set. For sheep, this is related to the inability to produce healthy meat, for goats it is related to the inability to do it profitably.

5 Conclusion

The French West Indies have a high concentration of persistently polluted soils which hinder their economic development and their potential of producing safe food for human consumption. This case study has raised several questions regarding the constraints that farmers must observe in order to produce and sell meat that is in line with the legal health and safety thresholds imposed by the law through the MRL. Our analysis adds to the scientific literature that deals with the economic impact of soil pollution on farmers' practices. In this field of research, this article is an attempt to couple conflicting economic and health-related targets.

Many studies have focused on the transfer of CLD from soil to plants (e.g. [4, 5, 6, 7]). It is also important to examine agricultural systems that produce animals on land contaminated by CLD. This article creates a new understanding of, both the impact and costs of CLD contamination in animals.

We have shown that the decisions farmers must make when choosing the most favourable species to raise are based on two determining factors: (i) the compatibility of the biotechnical and economic calendars and (ii) the size of the additional costs generated by the decontamination strategy that is implemented. Our results show the low profitability of breeding activities and call for further investigations to examine the measures to be observed to secure the income of farmers and discuss the incentives to perpetuate breeding and fattening activities.

In this article, the data are provided at the animal level. To go further in the analysis, reasoning at the farm level is relevant. This larger scale requires new strategies such as combining several animal species with different and potentially complementary production calendars. The forthcoming scale of reasoning will therefore involve a dynamic management of a species portfolio to guarantee the farm viability.

Notes

1. Because soil pollution caused by CLD persists over the course of several centuries, the contamination rate of the soil is assumed to be constant in this study.

2. We assume that there is no subsequent contamination after the decontamination phase is terminated. In other words, the decontamination phase is always followed by the slaughter of the animal. From a practical point of view, it makes no sense to let the animal graze on a contaminated plot after the decontamination phase has ended. If this were to happen, the level of contamination within the animal would start to increase once again and a subsequent decontamination phase might be necessary, thus adding unnecessary costs.

3. This rate is typically $\bar{\tau}_k$ if the contamination phase is long.

4. More specifically, we use data gathered in Guadeloupe Island.

5. This label was created in 2018 by the Natural Park of Martinique.

6. The case of the MRL 0, which means that the animal has never been contaminated, should be distinguished from the case of the MRL 0^+ which characterizes an animal that has gone through a decontamination process and contains very low levels of CLD. Detection methods vary between 0.02 and 2 μg per kg of fat according to the minimum thresholds for CLD detection [15]. The threshold used in our computations for the MRL 0^+ is 0.5 $\mu g \cdot kg^{-1}$.

7. Whenever there is more than one value for individuals of given species, we choose to keep the highest so that our results apply to all instances, i.e. by keeping the highest we are applying the precautionary principle.

8. Females are usually involved in reproduction cycles which encompass additional costs.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing Interests The authors declare no competing interests.

Author contributions P. Andrés-Domenech, V. Angeon, S. Bates wrote the main manuscript text and prepared all the figures and tables. C. Lesage collected the empirical data. All authors reviewed the manuscript.

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Availability of data and materials The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Appendix Rearing costs and benefits

Few data exist on breeding practices in Guadeloupe. [22] usually produces monographs on the functioning of livestock systems based on a small number of cases. Since the data produced by [22], the work of [16] is the most comprehensive work with a qualitative survey based on 37 livestock farmers.
In this appendix, we provide further details on rearing costs and benefits that are integrated in the economic calculation (See Table 3).

Cattle
Rearing practices implies both fixed costs and variable costs. In this section we list all the costs that intervene in the rearing of an animal (a male cow). The fixed rearing costs for cattle include: the purchase price, various fees (subscriptions), animal's identification tags.
Purchase price of an animal: The cost of buying a male cow at 8 months of age is expressed in EUR/animal. The price depends on its weight. The average weight of a male cow after weaning (at 8 months of age) is 175 kilograms [1]. The average price per cow equals 910 EUR/animal.
EDE contribution (in French, subscription to the Établissement de l'Élevage): The EDE is a development institute in charge of the identification and the traceability of animals. The subscription cost equals 8 EUR per animal, to be paid once a year (on the month in which the animal is bought and every twelve months thereafter).
GDS contribution (subscription to the Groupement de Défense Sanitaire - GDS): The GDS is a development institute that advises breeders on the animal's health status. The subscription cost equals 3 EUR to be paid once a year (one month after the animal is bought and then every twelve months).
Animal's identification tags: The cost of these tags amounts to 9 EUR and is paid once, two months after the animal is bought.
All the fixed costs noted above apply to all animals, regardless of whether they graze or they are kept in stalls. These costs amount to 930 EUR within the first year and 11 EUR for each subsequent year.
For animals' enclosure, the breeder bears specific costs (e.g. electric fence). They are equal to 608.21 EUR. One such structure lasts at least 10 years, which means that several cows may benefit from the same structure, although not at the same time. For each animal, the stabling cost is at most equal to 60.82 EUR. We attribute one tenth of the total cost to each animal.
If an animal is decontaminated in a stall, additional costs are paid. In practice, since the production units are small, farmers design rudimentary stalls with recovery material whose costs are not evaluated.

Two types of costs are distinguished: the monthly rearing cost and the additional monthly decontamination costs.
Monthly cost: This cost covers all the basics (i.e. fodder, feed concentrate, veterinary costs, etc.). It amounts to 14.58 EUR per month.
When the animal is undergoing the decontamination phase in a stall, food must be bought. Two supplementary costs are considered in this case: the cost of fodder and the cost of feed concentrate.
Cost of fodder: An animal placed in a stall eats 2 kilograms of fodder per day. A 240 kilograms fodder bale costs 80 EUR (i.e. 0.33 EUR . kg^{-1}). For an average month (30.5 days) this represents 20.3 EUR per animal and month.
Cost of feed concentrate: The average animal needs 0.6 kilograms of concentrate per day (i.e. 18.3 kilograms per month). A bag of animal concentrate (25 kilograms) costs 13.2 EUR. The cost of feed concentrate amounts to 9.7 EUR per month.
The variable rearing costs are thus 14.58 EUR per month when the animal is not undergoing decontamination and 44.58 EUR per month (14.58+20.3+9.7) when the animal is undergoing decontamination.
Financial inputs
The technical-economic schedule also includes financial inputs for the breeder. These are the slaughter premium, a marketing premium, a transport premium, European financial help (Programme of Options Specifically Relating to Remoteness and Insularity - POSEI), and the turnover.
Slaughter premium: 210 EUR/animal
Marketing premium: 300 EUR/animal
Transport premium: 40 EUR/animal
POSEI: 0.55 EUR . kg^{-1} of carcass
Turnover: 5.2 EUR . kg^{-1} of carcass

Following the same structure of decomposition of cost and benefits, the subsequent appendixes inform about the other animal species.

Sheep
Purchase price of an animal: The cost of buying a male sheep at 2.5 months of age is expressed in EUR/animal. The price depends on the weight of the animal. The average weight of a male sheep after weaning (at 2.5 months of age) is 13.7 kilograms [22]. The average price per sheep equals 4.8 EUR . kg^{-1} that corresponds to 66 EUR/animal.
EDE contribution: The subscription equals 8 EUR per animal and year. This cost is paid once a year, on the month in which the animal is bought and every twelve months thereafter.
GDS contribution: This subscription amounts to 3 EUR/year. To be paid once a year, one month after the animal is bought and once every twelve months.
Animal's identification tags: This cost equals 9 EUR to be paid once, two months after the animal is bought.
For animals' enclosure, the breeder supports specific costs (e.g. stall). They are equal to 50 EUR/animal. One such structure lasts at least 5 years, which

means that several animals may profit from the same structure.
All the fixed costs above apply to all animals. They amount to 123.76 EUR within the first year and 11 EUR for each subsequent year.
If an animal is decontaminated in a stall, additional costs are paid. We distinguish two types of costs: the monthly rearing cost and the monthly decontamination costs.
Monthly cost: This covers all the basics (i.e. fodder, feed concentrate, veterinary costs etc.). It amounts to 15.74 EUR per month.
When the animal is undergoing the decontamination phase in a stall, its food is bought. This adds cost of fodder and cost of feed concentrate.
Cost of fodder: An animal placed in a stall eats 2.5 kilograms of fodder per day. A 240-kilogram fodder bale costs 80 EUR (i.e. 0.33 EUR . kg^{-1}). For an average month (30.5 days), this represents 10.17 EUR per animal.
Cost of feed concentrate: After weaning, the average animal needs 0.1 kilograms of concentrate per day during 3 months. After this period, the animal is fattened during 3.5 months and eats concentrate and fodder at the rate of 0.3 kilogram of concentrate per day and 2.5 kilograms of fodder per day.
The average daily gain for animals kept in stalls is estimated at a level of 188 g/day. The average weight at the end of fattening is 33 kilograms. The average carcass weighs 14.6 kilograms. Fattening sheep are sold at the age of 9 months. The average sale price is estimated at 9.6 EUR . kg^{-1} of carcass, according to the data provided by the Réseau de références.
The variable rearing costs are thus 9.09 EUR/month when the animal is not undergoing decontamination and 15.74 EUR/month when the animal is undergoing decontamination.
Financial inputs
Contrary to breeders that rear cows, the financial inputs received by breeders for sheep are just the following: POSEI at a rate of 9 EUR . kg^{-1} of carcass and turnover at a level of 9.6 EUR . kg^{-1} of carcass.

Goats

Purchase price of an animal: The cost of buying a male goat at 2.5 to 3 months of age is expressed in EUR/animal. The price depends on the weight of the animal. The average weight of a male goat after weaning, at 2.5 months of age, is 7.87 kilograms [22]. The average price per goat equals 4.8 EUR . kg^{-1} that corresponds to 55.09 EUR/animal.
The following costs are strictly identical for goats and sheep (refer to Appendix on sheep for detailed figures): EDE contribution, GDS contribution, Animal's identification tags, Animals' enclosure.
All the fixed costs above apply to every animal. They amount to 113.09 EUR within the first year and 11 EUR for each subsequent year.
If an animal is decontaminated in a stall, additional costs are to be paid. We distinguish two types of costs: the monthly rearing cost and the monthly decontamination costs.
Monthly cost: This covers all the basics (i.e. fodder, feed concentrate, veterinary costs, etc.). It amounts to 2.64 EUR per month.

When the animal is undergoing the decontamination phase in a stall, fodder and feed concentrate must be bought.
Cost of fodder: An animal placed in a stall eats 2.5 kilograms of fodder per day. A 240-kilogram fodder bale costs 80 EUR (i.e. 0.33 EUR . kg^{-1}). For an average month (30.5 days) this represents 10.17 EUR per animal.
Cost of feed concentrate: After weaning, the average animal needs 0.1 kilogram of concentrate per day during 3 months. After this period, the animal is being fattened for 3 months and eats concentrate and fodder at the rate of 0.2 kilogram of concentrate/day and 2.5 kilograms of fodder/day.
Once they are 6 months old, goats are supplemented with concentrate and fodder at a rate of 0.3 kilogram of concentrate/day and 2.5 kilogram of fodder/day. The average daily gain for animals kept in stalls is estimated at 84 g/day. The average weight at the end of fattening is 23 kilograms, for an average carcass weight estimated at 10.5 kilograms. Fattening sheep are sold at the age of 9 months. The average sale price is estimated at 9.6 EUR . kg^{-1} of carcass, according to the data provided by the Réseau de références.
Fattening goats are sold at the age of 12 months. The average selling price is estimated at 12.1 EUR . kg^{-1} of carcass.
The variable rearing costs are thus 5 EUR/month when the animal is not undergoing decontamination and 7.51 EUR/month when the animal is undergoing decontamination.
Financial inputs
Financial inputs are strictly identical for goats and sheep. They integrate: POSEI at a rate of 9 EUR . kg^{-1} of carcass and turnover (12.1 EUR . kg^{-1} of carcass).

Pigs

Considering that pigs are not viable from a health viewpoint, economic computation is not worthwhile. That is the reason why no further details are provided for this species.

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