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DESCRIPTIVE ANALYSIS OF THE ENVIRONMENTAL IMPACT OF INTENSIVE RABBIT PRODUCTION

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Abstract: This descriptive literature review presents some elements that allow us to quantify the main contributions of rabbit farming to global warming, pollution (mostly nitrogen losses, airborne particulate matter), water footprint and biodiversity loss. As the majority of meat rabbits farmed in the world are raised in indoor cage systems, most studies only cover this production system. A single attempt has been made to quantify the environmental impact of an alternative system, based on rabbits grazing under photovoltaic panels. Although it provides some insights into possible alternatives, the results obtained are not based on real data. Regarding the contribution of rabbit production to global warming, the estimations of greenhouse gas emissions ranged from 3.13 to 3.25 kg of CO_2 eq. per growing rabbit over a 35-d period. No estimates are available for the whole system (all animal categories). Pollution associated with nitrogen losses varied between 40.1 and 59.1 g of N per kg of liveweight gain. Air pollution related to the airborne particulate matter (10 micron) varied from 0.082 to 0.045 mg per m^3, and there was no data available on the water footprint, which is likely to be between those observed for poultry and pig production. For biodiversity loss, there are no studies on the impact of rabbit production on wild life. This communication ends with a brief discussion of the possible alternatives and presents some technical perspectives for the rabbit sector.

Key Words: *Oryctolagus cuniculus*, greenhouse gas, water use, air quality, biodiversity loss.

INTRODUCTION

This brief review in not intended to be an exhaustive compilation of the environmental impacts of intensive animal (rabbit) production. Comprehensive texts on the subject are already available (Steinfeld *et al.*, 2006), and much of the mitigation strategies and policies have been addressed by the Intergovernmental Panel on Climate Change in recent years (https://www.ipcc.ch/srccl/).

As you will see, the literature available on the environmental impact of livestock production is vast and covers many areas, from technical solutions to policy. Ethics, moral philosophy and critiques of the organisation of the global economy and society are also present in the debate about what to do with animal (rabbit) farming. Some argue in favour for its abolition (Reese, 2018), while others clearly demonstrate the importance of farm animals to human societies (Porcher, 2011). Personally, I believe that it is possible to produce the necessary amount of high-quality animal products for every single person on this planet. I also believe that we can do it in an intelligent way. A way that respects the physical and mental integrity of every farmed animal, and properly values the work of both humans and animals involved in our food production chain. A way that preserves nature and guarantees food sovereignty for the current and future generations.

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To the date, I have no clear idea of how to achieve these goals. This brief descriptive analysis of the environmental impact of intensive rabbit production will certainly not solve these problems. What I can offer you here is a simple compendium of what is known about the rabbit industry. But I will try to give you some thoughts and perspectives on where we should focus our practices in the coming years. I hope you enjoy reading this work, as much as I have enjoyed writing it.

LITERATURE SEARCHING CRITERIA

The literature search was performed using the Web of Science advanced search query builder (https://www.webofscience.com/wos/woscc/advanced-search). The search period was set to January 1955 and February 2024. All results from the Web of Science Core Collection were checked. The selected editions were: A&HCI,

Table 1: Keywords used in the query syntax and number of documents retrieved.

Keywords	Searching query syntax *	Documents
Livestock AND		
Environmental impact	(TS=("Livestock production")) AND TS=("Environmental impact")	281
Greenhouse gas	(TS=("Livestock production")) AND TS=("Greenhouse gas")	761
Pollution	(TS=("Livestock production")) AND TS=("Pollution")	436
Pollution AND Waste	((TS=("Livestock production")) AND TS=("Pollution")) AND TS=("Waste")	88
Biodiversity	(TS=("Livestock production")) AND TS=("Biodiversity")	572
Water use	(TS=("Livestock production")) AND TS=("Water use")	144
Water pollution	(TS=("Livestock production")) AND TS=("Water pollution")	58
Air quality	(TS=("Livestock production") AND TS=("Air quality")	67
Rabbit AND		
Environmental impact	(TS=("Rabbit")) AND TS=("Environmental impact")	21
Greenhouse gas	(TS=("Rabbit")) AND TS=("Greenhouse gas")	17
Pollution	(TS=("Rabbit")) AND TS=("Pollution")	140
Pollution AND Waste	((TS=("Rabbit")) AND TS=("Pollution")) AND TS=("Waste")	19
Biodiversity	(TS=("Rabbit")) AND TS=("Biodiversity")	224
Water use	(TS=("Rabbit")) AND TS=("Water use")	5
Water pollution	(TS=("Rabbit")) AND TS=("Water pollution")	4
Air quality	(TS=("Rabbit")) AND TS=("Air quality")	13
Rabbit farming AND		
Environmental impact	(TS=("Rabbit farming")) AND TS=("Environmental impact")	4
Greenhouse gas	(TS=("Rabbit farming")) AND TS=("Greenhouse gas")	3
Pollution	(TS=("Rabbit farming")) AND TS=("Pollution")	1
Pollution AND Waste	((TS=("Rabbit farming ")) AND TS=("Pollution")) AND TS=("Waste")	0
Biodiversity	(TS=("Rabbit farming")) AND TS=("Biodiversity")	0
Water	(TS=("Rabbit farming")) AND TS=("Water")	3
Water use	(TS=("Rabbit farming")) AND TS=("Water use")	0
Water pollution	(TS=("Rabbit farming")) AND TS=("Water pollution")	0
Air quality	TS=("rabbit farming") AND TS=("Air quality")	0
Rabbit production AND		
Environmental impact	(TS=("Rabbit production")) AND TS=("Environmental impact")	4
Greenhouse gas	(TS=("Rabbit production")) AND TS=("Greenhouse gas")	3
Pollution	(TS=("Rabbit production")) AND TS=("Pollution")	1
Pollution AND Waste	((TS=("Rabbit production")) AND TS=("Pollution")) AND TS=("Waste")	0
Biodiversity	(TS=("Rabbit production ")) AND TS=("Biodiversity")	0
Water	(TS=("Rabbit production ")) AND TS=("Water")	10
Water use	(TS=("Rabbit production")) AND TS=("Water use")	0
Water pollution	(TS=("Rabbit farming")) AND TS=("Water pollution")	0
Air quality	(TS=("rabbit production") AND TS=("Air quality")	1

* Boolean expression and field tags (TS=Topic) from https://www.webofscience.com/wos/woscc/advanced-search

BKCI-SSH, BKCI-S, CCR-EXPANDED, ESCI, IC, CPCI-SSH, CPCI-S, SCI-EXPANDED and SSCI. The query syntax used in the sequential search and the number of documents retrieved (all types) are shown in Table 1.

From these sequential searches, a total of 560 documents (all types) were preselected based on their title. A second screening of all retrieved documents was carried out after reading the abstracts of each book chapter and peer-reviewed research paper. This second screening process resulted in a selection of 422 documents.

All peer-reviewed papers that specifically addressed the environmental impacts of "*rabbit farming*" or "*rabbit production"* were retained for analysis (n=20). Some papers on wild rabbits (n=5) or alternative rabbit production systems (n=7) were also included. From the remaining documents, covering several topics related to the environmental impact of livestock production, the most relevant articles from each decade were carefully examined (n=38).

The aim was to provide an overview of how rabbit production contributes to the environmental problems we face today, such as: greenhouse gas emissions, water footprint, particulate matter emissions or biodiversity loss. The concept of sustainability in rabbit production was briefly discussed.

BRIEF OVERVIEW OF FIVE DECADES OF RESEARCH ON THE ENVIRONMENTAL IMPACTS OF ANIMAL PRODUCTION

This paper is not intended to further assess the environmental impacts of animal (or specifically rabbit) production. Exactly 18 yr ago, Steinfeld *et al*. (2006) already produced a comprehensive document on the subject, *Livestock's long shadow: environmental issues and options*. In this book, the authors detailed the global contribution of the livestock sector to land degradation, climate change, water use and pollution and biodiversity loss. They discussed technical strategies designed to improve the efficiency of livestock operations and proposed some policy alternatives, such as properly pricing the use of land, water and other natural resources, to shed some light on livestock's long shadow. Since the publication of this book, the scientific literature on the subject has boomed, from 44 to around 364 peer-reviewed scientific papers (including only the articles preselected for this study).

As early as 1978, Hodge highlighted the external costs of livestock production (water pollution, cruelty to animals and nuisance: odour, sewage, pests, etc.) and the negative perception of livestock production by citizens in urban areas. According to Hodge (1978a), the main factors influencing complaints were related to the type of production, the number of animals and the techniques used (or not) to prevent pollution and other nuisances. For instance, intensive dairy and poultry production received most complaints. For pig farming, "*traditional*" farms (up to 250 animals) received no complaints while the so-called "*factory*" farms (over 1 500 pigs) were frequently criticised. In a second study, Hodge (1978b) noted the importance of having clear standards for measuring environmental impacts and argued for the adoption of policies to prevent pollution and nuisance. Since then, the Right-to-Farm Act (https://alec.org/model-policy/right-to-farm-act/), which was intended to protect farmers from nuisance lawsuits, has given "*big agribusiness a free pass to pollute and cause harm to people and our land*", said Diamond *et al*. (2022).

In the decade following the works of Hodge, only one article was retrieved from the literature. In this work, Conway (1987) introduced and described the properties of agroecosystems - "*an ecological system modified by human beings to produce food, fibre and other agricultural products"*. In his definition, the primary attributes of agroecosystems are: productivity, stability, sustainability and equitability. Together, these four properties define the social value of the agroecosystem. For Conway, productivity is the output of valued products per unit of resource input, stability is the constancy of production in the face of normal fluctuations and cycles in the environment, while sustainability is the ability of an agroecosystem to maintain its productivity in the face of major disturbances (erosion, declining market demand, etc.). Finally, Conway (1987) defined equity as the equitable distribution of the productivity among the human beneficiaries, which in the case of modern agricultural systems seems to favour a reduced number of actors. In Europe, the agriculture policy stated in 1957 under the European Economic Commission has favoured the larger, richer and more specialised farmers through a subsidy system based on production. Pollution, incidents caused by livestock or silage effluents, loss of amenity, recreational and conservation values of the countryside, and the degradation of ancient woodlands, chalk grasslands, herb-rich meadows, heaths, etc. are all side effects of a policy based on productivity alone (Conway,1987).

The nineties were a decade of bright works. Writing about the strategies for sustainable (poultry) production, Stenholm and Waggoner (1991) pointed out the responsibility of scientists to help the public understand the benefits and risks of all farming practices. They called for a scientific consensus and mentioned that any production system should stand the test of scientific scrutiny, economic analysis and social acceptance and impact. They also stated that (poultry) scientists should combine their experience and expertise with those of other biological and social sciences. The same being true for information and communication sciences. In itself, this openness to collaboration seems to be the key to achieving a more ambitious set of practices to reduce the impact of livestock production on natural resources.

For developing nations, sustainability could be achieved by improving the feed quality, genetic resources and animal health management (Kaasschieter *et al.*,1992). However, this technical improvement should be developed within the small-scale mixed farming systems that predominate in developing countries. Back to Europe, Atkinson and Watson (1996) identified the nitrogen load from animal wastes produced by industrial units of pig, poultry and dairy production as the major environmental problem in British lowlands. For these authors, the solution is simple: to develop systems that allow waste to be reused on primary crop production sites, similar to what is proposed by the circular bioeconomy or sustainable intensification approaches (Pretty and Bharucha, 2014). In short, Atkinson and Watson (1996) called for holistic farming systems that integrate livestock in a way that reduces the impact on the environment and wildlife (plant and animal) biodiversity.

Two interesting papers close the decade. Waltner-Toes (1996) introduced us to the concept of "*ecosystem health*" while Faye *et al.* (1999) extended this concept to "*agroecosystem health*". For Waltner-Toes (1996), the global agri-food system as it is organised is unsustainable: subsidies for high production in countries with low population densities in farming systems that are heavily dependent on energy and oil-based inputs to function. This author was very critical of using the "*hard system*" view to assess whether or not a production system is sustainable or not. For him, this method runs the risk of considering a production system to be sustainable simply because the current socioeconomic context dictates it: for example, "*the jobs of rural people may be considered as less important than the cheapness of urban food"*. To address this problem, he discussed some of the available frameworks before proposing a new one: '*ecosystem health*'. For him, "*health sciences ask the kind of questions that agroecosystems caretakers should be asking"*. Moreover, the language of health science (screening, diagnosis, risk factors and fitness) is well understood by the general public, providing *"a rare opportunity for citizens to speak about what they value subjectively and what they know objectively"*. Put simply, the concept of One Health as we know it today (World Health Organisation, 2017) is rooted in the ideas discussed by Waltner-Toes (1996) who said: "*definitions of ecosystem health and human community health, although still evolving, emphasise two components: an element of equilibrium, or balance and an element of potential or reserve".* Faye *et al.* (1999) went beyond the definition of "*ecosystem health*" and extended the concept to "*agroecosystem health*". In practice, it is just a matter of scale, where the system boundaries are broadened to include multiple dimensions (biophysical, social, economic) within a complex hierarchy (from the field to the biosphere) where health components (integrity and effectiveness) are present.

The literature reviewed in the period between 2000 and 2010 covered several subjects. It ranged from an economic modelling approach to find the best solutions to avoid environmental impacts of different livestock waste-management (Innes, 2000) to ethics in organic livestock production (Lund *et al.*, 2004). The concepts of "*land sharing*" (wildlife-friendly farming) and "*land sparing*" (minimising demand for farmland by increasing yields) were also introduced in this period, in a comprehensive work by Green *et al.* (2005). In the same year as the FAO publication *Livestock's long shadow*, Monteny *et al.* (2006) reviewed the greenhouse gas emissions and mitigation strategies for cattle, pig and poultry production. They identified the rumen and manure from swine and poultry as the main sources of methane (NH_4) emission from livestock. For nitrous oxide (N_2O), the main sources are: nitrogen fertilisers, manure applied to land and urine deposited by grazing animals. For these authors, technical solutions such as improving feed efficiency or on-farm biogas production should be used to reduce the greenhouse gas emissions. The era of technical solutions and direct comparisons between organic and industrial systems began. For Bokkers and de Boer (2009), although organic broiler production performed better on economic and social indicators (net farm income, workload, animal health and welfare and reduced use of antibiotics), the use of feed efficiency as the only criterion as a proxy of environmental impact systematically favoured the so-called "*factory*" farms. This period is concluded by the work of Verburg *et al.* (2009), who analysed the impact of agricultural trade liberalism on land use related greenhouse gas emissions. For these authors, liberalisation should increase the total greenhouse gas emissions by 6%, due to vegetation clearance for crop production.

The first papers on the environmental impact of rabbit meat production appeared in this decade. Calvet *et al.* (2008) estimated the efficiency of nitrogen use in rabbit production, Fortun-Lamothe *et al.* (2009) evaluated the contribution of intensive rabbit production to sustainable development, and Kaliste *et al.* (2002) and Cambra-López *et al.* (2010) presented the first results on the airborne particulate matter from rabbit farms. Estellés *et al.* (2009) developed a new method to measure greenhouse gas emissions from both rabbit metabolism and manure decomposition, and Estellés *et al.* (2010) measured the daily carbon emissions of fattening rabbits. The following year, Calvet *et al.* (2011) used a different method to characterise the indoor environment and the gas emissions in both commercial and experimental rabbit farms, while Franz *et al.* (2011) quantified the methane emissions from rabbits (and guinea pigs) fed exclusively on hay, observing a daily methane production of 0.2 L per rabbit.

The literature on the environmental impact of rabbit production continued until 2022. From this period, we can cite the work of Adell *et al.* (2012a and 2012b) on the emission, morphology and characteristics of particulate matter in rabbit farms, Estellés *et al.* (2014) and Dinuccio *et al.* (2019), who studied the greenhouse gas emissions from rabbit manure, or Biagini *et al.* (2021) on the potential of feed additives to reduce the ammonia and greenhouse gas emissions from rabbits. Predictions of nutrient flows and the environmental impacts of rabbit farming were studied by Méda *et al.* (2014) using a modelling approach and by Cesari *et al.* (2018), Pascaris *et al.* (2021) and Wang *et al.* (2022) using a life cycle analysis. Theau-Clément *et al.* (2016), using a multicriteria evaluation method, evaluated the sustainability of two alternative rabbit breeding systems.

As the majority of farmed rabbits are housed indoors in cages, the literature produced on the environmental impact of rabbit farming is limited to this production system. There is only one article that attempted to assess the environmental impact of two alternative rabbit production systems (Pascaris *et al.*, 2021). In itself, this work sheds some light on the possible alternatives, but its scientific and social value can be questioned. In fact, the systems studied were based on the prospective work of Lytle *et al.* (2021), who proposed raising rabbits under solar panels.

The literature reviewed also covered policy. Gerber *et al.* (2010) reviewed several policy instruments (taxes, subsidies, emissions trading, voluntary mitigation efforts) to reduce the greenhouse gas emissions from livestock. Golub *et al.* (2013) studied the impacts of global climate policies on livestock, land use change, livelihoods and food security. They found, for example, that fiscal policies targeting only *Annex I* countries (https://unfccc.int/process-and-meetings/what-are-parties-non-party-stakeholders) may result in an expansion of agricultural land in non- *Annex I* nations, leading to an increase in emissions from deforestation.

Consumer behaviour and preferences also play an important role in policy effectiveness. Schulze *et al.* (2023) showed a strong public preference for a sustainable transformation of livestock production and provided evidence that reducing livestock numbers is an acceptable path from the public's perspective. According to these authors, the greenhouse gas abatement potential of livestock reduction can be huge: it could account for up to 45% of the whole sector, including reductions in emissions from land use change, fertiliser and pesticide production and use, manure excretion and application, feed processing and transport. These figures appear to contradict those presented by Leroy *et al.* (2022). For these authors, reducing livestock numbers based on the argument that healthy diets are low in red meat and saturated fat seems flawed, and in the context of overall Western lifestyle footprint, a large reduction in meat intake would result in a 2% to 6% reduction on the carbon footprint (*e.g.*, 12 t CO_2-eq. per person annually). Leroy *et al.* (2022) also questioned the claims about the impact of livestock on planetary health. Based on their review, those claims are not justified. However, these authors recognised the importance of understanding that the environmental impact of livestock production depends on the region, ecosystem and practices involved.

GREENHOUSE GAS EMISSIONS & NITROGEN LOSSES IN RABBIT FARMING

The available data on greenhouse gas emissions and nitrogen losses in rabbit production systems are summarised in Table 2. The emissions were classified according to the emission source (farm, animal or manure), the methodology used to estimate (life cycle analysis or modelling) or to measure (gas emission rates, nitrogen balance, and flux or fermentation chambers) these emissions according to the farm type (average Italian or French production system, theoretical farm with or without photovoltaics, and commercial or experimental farms).

Farm emissions

Cesari *et al*. (2018) used a life cycle analysis to estimate the total greenhouse gas emissions from a theoretical average Italian rabbit meat production farm. They determined the values of the input variables using data from the literature and considered the feed conversion ratio as the only variable related to production efficiency and environmental impact. After modelling three scenarios of mortality rates (5%, 10% and 20%) in the fattening period (only), the total greenhouse gas emissions were estimated to vary between 3.78 and 4.04 kg of CO_2 eq. per kg of liveweight produced. The authors compared the results with those of other monogastric species (chicken and pig) and concluded that the environmental impact of an average Italian rabbit meat farm is comparable to that of a pig farm. Although this is a positive result, it is possible that some of the postulates used in the analysis may misrepresent the actual environmental impact of rabbit meat production. In their analysis, Cesari *et al*. (2018) excluded the emission from the construction and maintenance of infrastructure (buildings, cages, etc.) as well as the emission from the use of antibiotics and hormones. Furthermore, emissions related to the manure were downgraded. It was assumed that all manure produced was used in the production of corn on the same farm.

Despite the modelling choices made by Cesari *et al*. (2018), the most interesting result is the high contribution of feed production to climate change (about 71.2% of the total CO_2 eq. emissions), mainly related to the use of fossil fuels for crop production and the transport of feed ingredients from other countries (soybean meal from Brazil and sugarcane molasses from Thailand). Of the various environmental impacts assessed by Cesari *et al*. (2018), land use change had a negative score. This was related to the use of alfalfa in the diets, a crop that sequesters carbon compared to arable crops. A land use of 12.5 m^2 per kg of liveweight produced was also estimated by the authors.

The only on-farm study presenting actual measurements of greenhouse gas emission from commercial and experimental rabbit farms was conducted by Calvet *et al*. (2011). They measured the real-time emissions of ammonia, carbon dioxide and nitrous oxide in three rabbit farms in eastern Spain (two commercial farms and one experimental farm). Methane emissions were also measured, but could not be determined as readings below 10 ppm are strongly influenced by the air moisture values. All measurements were made with a multi-gas photoacoustic analyser and the emissions of NH_3, CO_2 and N_2O were obtained by calculating the emission rates per animal. Farm emissions included those from the animals and their manure together. In addition, emissions from breeding females and growing rabbits were calculated separately. After converting the results to kg of CO_2 eq. per animal over one year (using the greenhouse gas equivalencies calculator from the U.S.A. Environmental Protection Agency: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator), the total greenhouse gas emissions were 164 kg of CO_2 eq. per animal per year. Each female rabbit emitted 134 kg of CO_2 eq. per year, while growing rabbits emitted around 30 kg of CO_2 eq. per animal per year (or about 2.80 kg of CO_2 eq. per animal considering a fattening period of 35 d). Although the values obtained for growing rabbits (rough estimation assuming a fattening period of 35 d) were below those reported by Cesari *et al*. (2018), emissions from other sources, rather than the direct emissions from the animal metabolism and manure decomposition, were not taken into account by these authors.

The remaining studies assessing the environmental impacts at farm level (Méda *et al*., 2014; Pascaris *et al*., 2021; Wang *et al*., 2022) present different greenhouse gas emissions values. Using dynamic modelling, Méda *et al*. (2014) estimated the emissions of ammonia, nitrous oxide and methane from a typical French rabbit farm with 605 female rabbits. They also considered two manure management systems: slurry or deep pit. The values in Table 2 are the range of NH_3, N_2O and CH_4 from the two manure management systems. When converted to CO_2 eq., the estimated emissions were 0.498 and 0.536 kg of CO_2 eq. per kg of liveweight produced in the slurry and in the deep pit systems, respectively. These figures are lower than those obtained by Cesari *et al*. (2018), using a life cycle assessment, and Calvet *et al*. (2011), using direct on-farm gas emission measurements. The observed differences between these studies may be related to the methodology used, the assumptions of each model and the system boundaries.

Pascaris *et al*. (2021) compared three systems: grazing rabbits under photovoltaic panels, indoor raised rabbits heated with energy produced on-site from photovoltaic panels, and indoor rabbits heated with energy from fossil fuels. This theoretical photovoltaic system, conceptualised by Lytle *et al*. (2021), cannot be compared to the conventional

Table 2: Greenhouse gas (GHG) emissions from rabbit production.

GHG emissions	Units	Main emissions	Source	Methodology	Farm type	Reference
3.78 to 4.04	Kg of CO_2 eq. per kg of liveweight	Feed ~ 70.0%	Farm	Life Cycle - estimation	Average Italian - whole system	Cesari et al. 2018
199.7	Kg of CO_2 eq. per kg of liveweight	Solar ~ 99.9%	Farm	Life Cycle - estimation	Theoretical - pasture photovoltaic	Pascaris et al. 2021
651.6	Kg of CO_2 eq. per kg of liveweight	Feed ~ 69.3%	Farm	Life Cycle - estimation	Theoretical - indoor photovoltaic	Pascaris et al. 2021
13619.9	Kg of CO_2 eq. per kg of liveweight	Energy ~ 96.7%	Farm	Life Cycle - estimation	Theoretical - indoor no photovoltaic	Pascaris et al. 2021
30.6 to 44.7	Kg of CO_2 eq. (total emissions)	Feed over 85%	Farm	Life Cycle - estimation	Rex fur production system	Wang et al. 2022
11.3 to 13.7	g of NH_3 per kg of liveweight	Not reported	Farm	Modelling - estimation	Average French - whole system	Méda et al. 2014
0 to 0.17	g of N_2O per kg of liveweight	Not reported	Farm	Modelling - estimation	Average French - whole system	Méda et al. 2014
17.8	g of CH_4 per kg of liveweight	Not reported	Farm	Modelling - estimation	Average French - whole system	Méda et al. 2014
38.7 to 65.6	mg of NH_3 per hour and animal	Not reported	Farm	Gas emission rates	Commercial - reproductive does	Calvet et al. 2011
4004 to 17 820	mg of CO_2 per hour and animal	Not reported	Farm	Gas emission rates	Commercial - reproductive does	Calvet et al. 2011
0 to 20.8	mg of N_2O per hour and animal	Not reported	Farm	Gas emission rates	Commercial - reproductive does	Calvet et al. 2011
3.5 to 12.1	mg of NH_3 per hour and animal	Not reported	Farm	Gas emission rates	Commercial - growing rabbits	Calvet et al. 2011
1180 to 3880	mg of CO_2 per hour and animal	Not reported	Farm	Gas emission rates	Commercial - growing rabbits	Calvet et al. 2011
0 to 2.0	mg of N_2O per hour and animal	Not reported	Farm	Gas emission rates	Commercial - growing rabbits	Calvet et al. 2011
1.12 to 1.40	litres of CO_2 per hour	Not reported	Animal	Flux chamber	Experimental - growing rabbits	Estellés et al. 2009
1.35 to 2.61	litres of CO_2 per hour	Not reported	Animal	Flux chamber	Experimental - growing rabbits	Estellés et al. 2010
0.12 to 0.28	litres of CH_4 per day	Not reported	Animal	Flux chamber	Experimental - pygmy rabbits	Franz et al. 2011
40.1 to 42.4	g of N per kg of liveweight	Not reported	Animal	Nitrogen balance	Experimental - growing rabbits	Calvet et al. 2008
57.0 to 59.1	g of N per kg of liveweight	Not reported	Animal	Nitrogen balance	Experimental - growing rabbits	Dinuccio et al. 2019
2.95 to 3.26	mg of NH_3 per hour	Not reported	Manure	Flux chamber	Experimental - growing rabbits	Estellés et al. 2009
216.9 to 272.4	mg of CO_2 per hour	Not reported	Manure	Flux chamber	Experimental - growing rabbits	Estellés et al. 2009
17.8 to 26.4	mg of NH_3 per hour and m^2	Not reported	Manure	Flux chamber	Experimental - growing rabbits	Estellés et al. 2014
1.93 to 2.53	mg of N_2O per hour and m^2	Not reported	Manure	Flux chamber	Experimental - growing rabbits	Estellés et al. 2014
7.5 to 10.8	mg of CO_2 per hour and m^2	Not reported	Manure	Flux chamber	Experimental - growing rabbits	Estellés et al. 2014
16.4 to 18.5	mg of CH_4 per hour and m^2	Not reported	Manure	Flux chamber	Experimental - growing rabbits	Estellés et al. 2014
212 to 257	g of CO_2 eq. per kg of manure	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Dinuccio et al. 2019
2.70	mg of CH_4 per g of manure	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Hidayat et al. 2021
143.7 to 246.7	g of NH_3 per m^2	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Biagini et al. 2021
1.04 to 1.60	g of N_2O per m^2	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Biagini et al. 2021
1779 to 2533	g of CO_2 per m^2	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Biagini et al. 2021
22.8 to 35.2	g of CH_4 m^2	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Biagini et al. 2021
3498 to 4226	g of CO_2 eq. m^2	Not reported	Manure	Fermentation chamber	Experimental - growing rabbits	Biagini et al. 2021

rabbit production systems present in Europe. In the case of China, Wang *et al*. (2022) estimated the environmental impacts of a Rex rabbit industry chain. In this study, the authors aimed to assess the benefits of a circular industry chain. After modelling two scenarios, one that integrated a biogas power plant for manure treatment and one that outsourced manure treatment without recycling it, a cradle-to-gate life cycle analysis was performed. The global warming potential, expressed in kg of CO_2 eq. was estimated at 30.6 and 44.7 kg of CO_2 eq. for the scenarios with and without biogas manure treatment, respectively. Wang *et al*. (2022) observed a large contribution of feed cultivation and the electric energy consumption in the feed processing stages on greenhouse gas emissions, as well as the other environmental impact categories. In summary, feeding accounted for over 85% of the CO_2 eq. emissions, in a manner consistent with the findings of Cesari *et al*. (2018). Wang *et al*. (2022) also observed that the use of a biogas power plant contributed to a reduction in the global warming potential, as a result of a reduction in the consumption of chemical fertilizers, pesticides and external electric power.

The greenhouse gas emission values vary widely between the studies at farm level. The differences observed are related to the choice and fine-tuning of the parameters used in the life cycle analysis, to the model assumptions and to the boundaries of the system considered in each study. For example, differences in carcass weight, feeding strategy (adoption of feed restriction or not) and on other parameters such as the reproductive performance of rabbit females (fertility, culling and/or mortality, etc.) will affect the results of a life cycle assessment. In terms of system boundaries, the inclusion or exclusion of a specific treatment of manure to produce part of the cereals used in the rabbit feed also influences the results, as does the inclusion or exclusion of the slaughter process in the calculations.

Despite its limitations, the life cycle analysis provides information on the different compartments that are the main contributors to greenhouse gas emissions. In the case of rabbit meat production, this method shows that the vast majority of CO_2 eq. emissions are associated with the fossil fuels used in feed production (Cesari *et al*., 2018 and Wang *et al*., 2022). This tool could be further improved by considering direct emissions data from multiple rabbit farms within a single (or multiple) country, as done by Calvet *et al*. (2011), or by using real emissions data from rabbit farms (Estellés *et al*., 2009 and 2014) instead of using standard emissions coefficients. For Goglio *et al*. (2023), this method still lacks accuracy and robustness in addressing sustainability across livestock systems and products. For them, harmonisation is needed.

Modelling approaches are also useful. They help us to understand certain phenomena, but their use should be limited to describing systems that are close to the reality, as done by Méda *et al*. (2014). Analyses based on theoretical systems can also help us to understand future and alternative systems. However, the lack of real data can lead to uncertain estimates, as in the case of Pascaris *et al*. (2021).

The use of real-time greenhouse gas emissions from the rabbit metabolism (respiration, assimilation, excretion, etc.) and from manure decomposition should also be considered. Their use should be preferred when analysing the global warming potential of conventional and alternative rabbit production systems.

Animal emissions

Some authors (Calvet *et al*., 2008; Estellés *et al*., 2009; Estellés *et al*., 2010; Franz *et al*., 2011; Dinuccio *et al*., 2019) have addressed emissions from the perspective of rabbit metabolism. None of the studies performed have characterised the greenhouse gas emissions of adult animals.

Estellés *et al*. (2009 and 2010), using a flux chamber designed to measure rabbit gas emissions, recorded individual emissions ranging from 1.12 to 2.61 litres of CO_2 per hour. Considering a fattening period of 35 d and a daily CO_2 emission of 47.5 litres per rabbit (assuming an average emission of 1.98 litres of CO_2 per hour for a rabbit of 1.24 kg; Estellés *et al*. 2010), the CO_2 eq. emissions of a single rabbit can reach 3.05 kg of CO_2 eq. in 35 d (because 1 m^3 of CO_2 weights 1.84 kg). This is in line with the estimations from Calvet *et al*. (2008).

Using a flux chamber, Franz *et al*. (2011) measured the CH_4 emission from pygmy rabbits fed on a hay diet. Enteric CH_4 emissions varied from 0.12 to 0.28 litres of CH_4 per day, which is lower compared to other mammalian herbivore species (Clauss *et al*., 2020). After assuming that 1 m^3 of CH_4 weighs 0.72 kg, a single rabbit should produce between 0.003 and 0.007 kg of CH_4 in 35 d, which represents between 0.084 and 0.196 kg of CO_2 eq. Adding up the estimations calculated from the data of Estellés *et al.* (2010) and Franz *et al.* (2011), a single growing rabbit should produce between 3.13 and 3.25 kg of CO_2 eq. in 35 d.

In addition to the greenhouse gas emissions measured at animal level, nitrogen losses were measured in growing rabbits by Calvet *et al.* (2008) and Dinuccio *et al.* (2019). Calvet *et al.* (2008) found excretion values between 40.1 and 42.4 g of N per kg of liveweight while Dinuccio *et al.* (2019) observed higher values, ranging from 57.0 to 59.1 g of N per kg of liveweight. The higher nitrogen excretion found by Dinuccio *et al.* (2019) may be related to the nitrogen content of the rabbit feeds: 28.4 g of N per kg feed compared to 25.9 g of N per kg of feed (on average) in the feeds used by Calvet *et al.* (2008).

Greenhouse gas emissions at animal level are consistent across the few studies available. As mentioned above, real-time measurements are preferable to averages and proxies. However, further development is needed. There is a lack of information on emissions from adult reproducing animals. There is also a lack of knowledge on the contribution of genetics, nutrition and veterinary practices to greenhouse gas emissions at animal level. Much work is needed in these areas.

Manure emissions

Emissions from rabbit manure were determined by two methods: flux chamber (Estellés *et al.*, 2009 and 2014) or fermentation chamber (Dinuccio *et al.*, 2019; Hidayat *et al.*, 2021; Biagini *et al.*, 2021). After placing manure samples in a flux chamber, the NH_3 and CO_2 emissions from fresh manure ranged from 2.95 to 3.26 mg of NH_3 per hour and from 216.9 to 272.4 mg of CO_2 per hour (Estellés *et al.*, 2009).

In an attempt to reduce the manure emissions, Estellés *et al.* (2014) added calcium superphosphate powder to the manure pits twice a week at a dose of 50 g per m^2. Although not statistically significant, the addition of this additive reduced the CO_2 emission from 10.81 to 7.45 g per hour per m^2 and the N_2O emissions from 2.53 to 1.93 mg per hour per m^2. On the contrary, CH_4 emissions increased from 16.37 to 18.45 mg per hour per m^2. When these values were converted to CO_2 eq., the daily emissions per m^2 were, on average, 680 g of CO_2 eq. with the additive and 978 g of CO_2 eq. without the additive.

Using a different method and metrics, Dinuccio *et al.* (2019) found manure emissions between 212 and 257 g of CO_2 eq. per kg of manure, while Biagini *et al.* (2021) reported daily manure CO_2 eq. emissions between 194 and 235 g per m^2. These values were lower than those reported by Estellés *et al.* (2014). The different results between Estellés *et al.* (2014) and Biagini *et al.* (2021) may be related to the different methodologies: 24-h of flux chamber measurements versus 18 consecutive days from manure samples placed in a fermentation chamber, respectively.

Hidayat *et al.* (2021) designed a fermentation chamber using PVC tubes. After placing samples of manure from different species (buffalo, chicken, cow, duck, goat and rabbits) they measured the CH_4 emissions for eight consecutive weeks. The aerobic digestion of duck manure produced the highest amount of methane (98.0 mg of CH_4 per g of manure). It was followed by buffalo (21.9 mg of CH_4 per g of manure), cow (20.32 mg of CH_4 per g of manure), chicken (18.0 mg of CH_4 per g of manure) and goat manure (6.01 mg of CH_4 per g of manure). Rabbit manure produced the lowest amount of all measured species, about 2.7 mg CH_4 per g of manure.

Direct measurements of greenhouse gas emissions from rabbit manure are also scarce. Although the results appear to be consistent among the available studies, the influence of the genetics, nutrition or manure management practices can alter the emission values. Real data from an array of farms with different genotypes, nutrition strategies and manure treatment practices are required. In spite of this information, studies aiming to describe the potential of rabbit manure use in crop and grassland systems should be further developed. Sustainable strategies for rabbit manure recycling should be designed on a whole-farm perspective, as in the case of other species (Petersen *et al.*, 2007; Petersen *et al.*, 2013).

PARTICULATE MATTER CONCENTRATION & EMISSIONS

The current data on particulate matter concentrations and emissions from rabbit farms is limited. Adell *et al.* (2012a) surveyed two rabbit farms: a fattening facility and a breeding farm, both of which had manure accumulated below the cages for three to four weeks. After 15 d of measurement, the concentration of particulate matter in the fattening facility was 0.082 and 0.012 mg per m^3 of particulate matter of size 10 and 2.5 microns, respectively. In the breeding farm, the air concentrations of particulate matter of sizes 10 and 2.5 microns were 0.048 and 0.012 mg per m^3, respectively. A variety of activities, including floor sweeping, animal handling and the use of pressurised water to clean the cages, were identified as the primary sources of particulate matter emissions (most 10 microns) in the fattening facility. In the breeding farm, sweeping and burning hair were the main activities contributing to particulate matter emissions of both sizes. In addition, the fattening unit appeared to emit more particulate matter outside the farm (on average, 0.52 and 0.02 g per hour of 10- and 2.5-micron particulate matter, respectively) than the breeding unit (on average, 0.33 and 0.06 g per hour of 10- and 2.5-micron particulate matter, respectively). This was due to the very high animal densities in the fattening unit.

In comparison to other species, the overall concentration of particulate matter found in rabbit farms is relatively low. In poultry and pig farms, for example, particulate matter emissions range from 0.05 to 15.3 mg per m^3 for inhalable and from 0.03 to 1.9 mg per m^3 for respirable particulate matter. From a regulatory standpoint, the emissions observed in rabbit houses are below the legal thresholds (Adell *et al*., 2012a).

Despite the reduced level of particulate matter found in rabbit rooms, its origin is diverse. This includes fur, skin particles, faeces, urine, bedding and disinfectants (Kaliste *et al*., 2002). In addition, it can carry ammonia, contain heavy metals, absorb odorants and transport bioaerosols such as bacteria (both gram-positive and gram-negative), fungi, viruses and even bioactive compounds like antibiotic particles (Cambra-López et al., 2010; Adell et al., 2012b). The combination of these factors may potentially increase the health risks for both animals and farmers. The environmental impacts associated with particulate matter emissions from livestock (including reduced visibility, vegetation stress and ecosystem change) represent an additional risk that has not yet been assessed.

Although the studies conducted in rabbit houses resulted in low particulate matter emissions, further investigation is required to better characterise the bioaerosols (bacteria and viruses) and antibiotics present in these particles. The characterisation of emissions from different farm typologies (purpose, animal density, building dimensions and other technical specifics, etc.) and production systems (outdoor grazing systems, for example) is of great interest. The absence of this information precludes any meaningful evaluation of the environmental impacts associated with rabbit production.

WATER FOOTPRINT

Before diving into the topic of water footprints, it is important to provide some definitions. Due to the different sources and uses of water, the water footprint is colour-coded into three categories: blue, green, and grey water (Mekonnen and Hoekstra, 2012). The blue water footprint is the volume of surface and groundwater required to produce one unit of product. The green water footprint is the volume of rainwater lost to evapotranspiration. The grey water footprint is the volume of freshwater required to assimilate the pollutant load based on existing ambient water quality standards.

Using data from the Food and Agriculture Organisation of the United Nations and from the literature, Mekonnen and Hoekstra (2012) estimated water footprints for several animal products: beef, sheep, goat, pig and chicken meat, eggs, milk, butter, milk powder, cheese and leather. The green, blue and grey water footprints for some of these products, according to the production system, are illustrated in Figure 1.

At first sight, the water footprint of grazing systems is higher than that of mixed and industrial systems (all products). The picture changes when the green (rainfall) water footprint is excluded. With the exception of poultry products, the blue and grey water footprints increase from grazing to industrial systems (Figure 1B). In their analysis, Mekonnen and Hoekstra (2012) found that 98% of the water footprint comes from feed. Drinking water, service water and feed-mixing water only account for 1.1, 0.8 and 0.03% of the total water footprint, respectively. Focusing on the blue water footprint in grazing systems, it accounts for 3.6% of the total footprint, with 33% of this consumption being related to drinking and service-water use. In contrast, the blue water footprint in industrial systems accounts for 8% of the total water footprint.

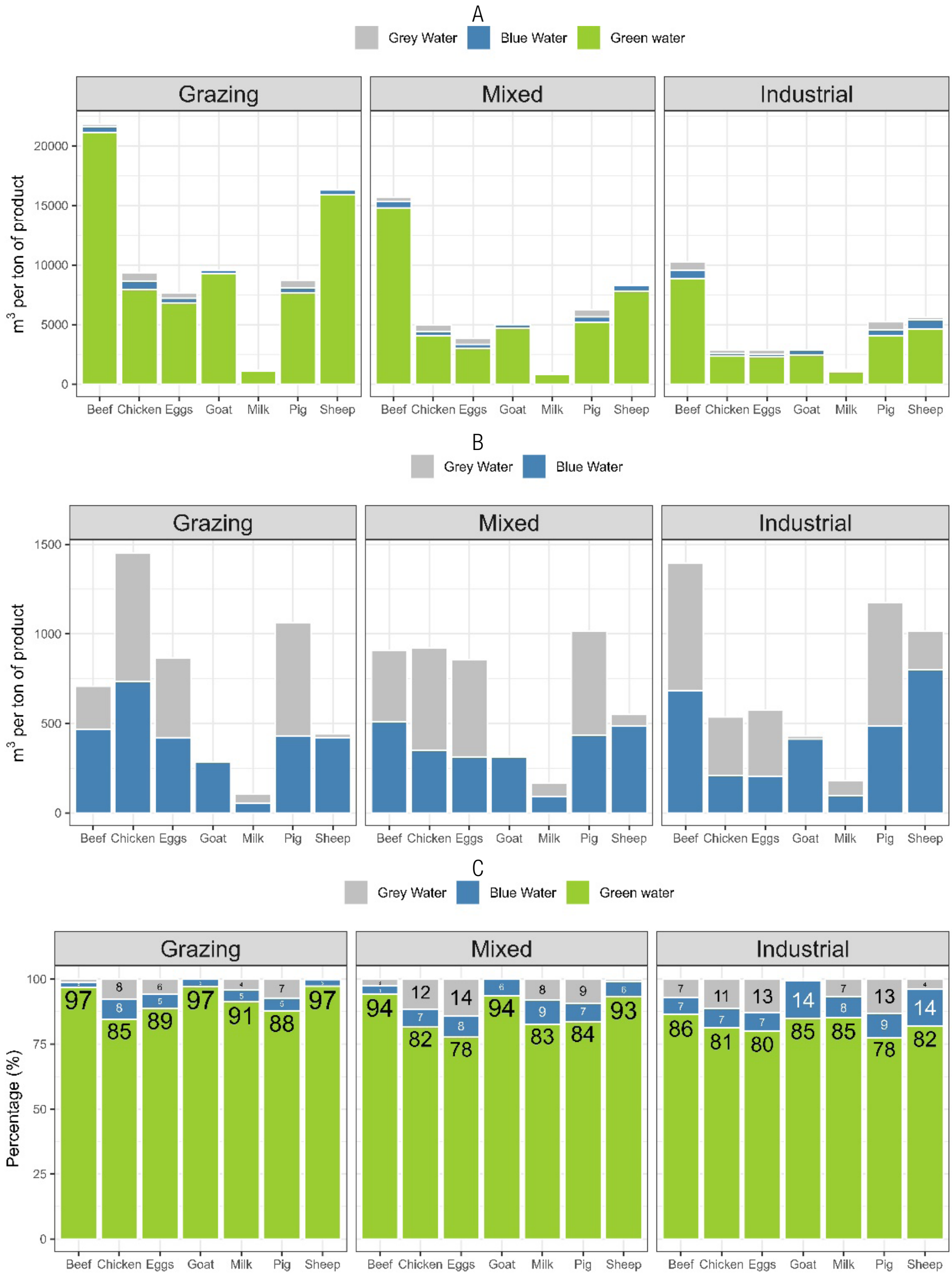

Figure 1: Volume of green, blue and grey water footprint per unit of animal products produced (A and B) and as a percentage of the total water footprint (C) according to the production system (Grazing, Mixed or Industrial). Adapted from Mekonnen and Hoekstra (2012).

The water footprint figures presented by Mekonnen and Hoekstra (2012) are very comprehensive. However, some striking points should be mentioned. Animal waste and water pollution from feed crop production other than nitrogen leakage were not included in the grey water footprint estimations. In addition to the underestimation of the grey water footprint, this category is often more important in intensive production systems. Ran *et al*. (2016) reviewed the methods used to assess water resource use in livestock production. For these authors, the grey water concept is a virtual water proxy of the volume of water required to assimilate pollutants and abate water quality degeneration, and due to the nature of this measure, it should not be added up with green and blue water uses.

In both studies (Mekonnen and Hoekstra, 2012; Ran *et al*., 2016), animal feed production is cited as the main factor contributing to water use. While Mekonnen and Hoekstra (2012) mention that animal farming based on crop residues, wastes and roughages to feed animals are the ones that put the lowest pressure on freshwater systems, Ran *et al*. (2016) mention systems where animals are grazed on marginal land that has few alternative uses and little socioeconomic value.

Although life cycle assessment studies fail to account for the majority of consumptive green water use, this approach highlights the importance of linking water resource use to local impacts and local water stress (Ran *et al*., 2016). For the rabbit sector, this is the only approach available. For instance, Cesari *et al*. (2018) estimated that 1.13 m^3 of water eq. is depleted to produce one kilogram of liveweight. These figures, however, are not comparable to the water footprint studies.

Despite the lack of data on the water footprint of meat rabbit production, the common use of crop residues (*e.g.,* cereal straw), by-products (*e.g.,* beet pulp) and coarse materials (*e.g.*, soybean hulls) in rabbit feed should contribute to placing the water footprint of industrial rabbit meat production somewhere between poultry products and pork. Studies are needed to fill the knowledge gap on water footprint of both industrial and alternative rabbit production systems.

BIODIVERSITY LOSS

Land use change, habitat degradation, pesticide use, and pollution are among the main factors associated with livestock impact on biodiversity (Green *et al*., 2005; Broom *et al*., 2013). Green *et al*. (2005) proposed two methods to balance the trade-off between food production for a growing human population and biodiversity conservation: land sparing and land sharing. Land sparing focuses on increasing yields on land already used for agriculture, thereby reducing the need to convert intact habitats for food/feed production. The concept of land sharing, on the other hand, includes the maintenance of natural habitat patches, the extensive food production on semi-natural habitats and the adoption of practices that minimise the negative effects of fertilisers and pesticides.

Looking at rangeland ecosystems, Alkemade *et al*. (2013) suggested that increasing yields in mixed crop-livestock systems in regions where productivity is still low is the best alternative to save land for nature. However, in regions where technology is advanced and productivity is already high, no positive effect of increased productivity on biodiversity can be expected (Alkemade *et al*., 2013). In addition, these authors pointed to the risks of technology-driven approaches, as they can lead to the loss of traditional cultures and knowledge, and to the degradation of abandoned land (unless a specific restoration programme is designed).

Although it may seem counterintuitive, efficient livestock production with high biodiversity and good animal welfare is possible (Broom *et al*., 2013). This can be achieved in agroforestry systems, which combine livestock production with native shrubs, trees and edible plants, where animals feed exclusively on plant resources that are not used for human consumption. When properly designed and managed, these complex agroecosystems favour species that act as biocontrols for pests and diseases, farmers find work more satisfying and biodiversity is enhanced (Broom *et al*., 2013). For these authors, with good management, agroforestry systems can replace industrialised, simplified systems and reduce agricultural expansion into protected areas (sharing farmland with wildlife while preserving land for nature; Pearse, 2018).

In the complex debate of the opposing worlds, where some advocate intensifying food production to save land for nature, while others argue that working with nature in complex agroecosystems is the solution, Kremen and Merenlender (2018) plead for a global landscape management in a matrix that works for biodiversity and for people. For them, a holistic approach is needed to reduce deforestation, which is mainly associated with growing crops to feed farm animals.

Biodiversity and environmental costs of intensive food production practices are well described by Tilman *et al*. (2002). High-density livestock systems, for example, can increase the incidence and promote the emergence of new diseases, often antibiotic-resistant, making the system vulnerable to catastrophic losses of animals to disease (Tilman *et al*., 2002). Pastoral systems, on the contrary, rely on ecosystem services and avoid many of the problems of confinement production. Pastured animals forage on plants growing in a field and plant growth is favoured by animal wastes. Ruminants and other domestic herbivores are capable of converting low quality roughage into high-quality animal products. In summary, well designed and correctly managed grassland-herbivore ecosystems are an efficient and sustainable method of producing high-quality food (Tilman *et al*., 2002).

To my knowledge, there are no studies quantifying the impact of rabbit farming on biodiversity loss. However, the main impact of European rabbit farming on biodiversity may be related to the deforestation to grow protein crops to feed the animals, mainly soya. This commodity and other flagship products are highly controversial and are subject to national regulations. For example, in 2018, the French government adopted a national plan to combat the importing of products from unsustainable deforestation (https://www.deforestationimportee.ecologie.gouv.fr/en/sndi/article/sndi).

In the absence of a precise knowledge of the impact of rabbit farming on biodiversity, several studies have described the contribution of wild rabbits to biodiversity. According to Gálvez-Bravo *et al*. (2009), the occurrence of four lizard species was associated with the presence of rabbit burrows, as they were only found in open pastures where rabbit burrows were present. The intense activity of rabbits around their burrows, the construction of latrines and their grazing behaviour cause a floristic change that promotes a particular heterogeneity in the herbaceous community, contributing to the beta diversity of the ecosystem (Gálvez-Bravo *et al*., 2011). The high quality of rabbit droppings (high carbon and high nitrogen to phosphorus ratios: 462 and 17.4, respectively) maintained the most diverse plant community when compared to the excretions of other herbivores (European bison, cow, horse and fallow deer) in a mesocosm experiment (Valdés-Correcher *et al*., 2019).

Wild rabbits also tend to increase habitat complexity and heterogeneity, favouring the abundance and/or richness of plant species through foraging, seed dispersal and soil fertilisation (Delibes-Mateos *et al*., 2008). Rabbits are also an important food source for several species of raptors, such as the Iberian lynx, the Spanish imperial eagle and several small birds of prey and generalist carnivores. Based on the multiple functional roles and ecosystem processes and patterns that are provided by the presence of rabbits in the Mediterranean scrubland, Delibes-Mateos *et al*. (2007 and 2008) characterised the European rabbit as a keystone species for this ecosystem in southwestern Europe.

In the light of the benefits of wild rabbits to the biodiversity of several plants and animal species, alternative farming integrating the rabbits as an herbivore in grasslands systems may be of interest. In France, pasture-based and organic rabbit production systems appear to be a promising way of farming (Gidenne *et al*., 2024), with technical results comparable to conventional indoor systems Fetiveau *et al*. (2021, 2023a). This outdoor pasture-based system also favoured the expression of specific behaviours not observed in cage systems, with grazing being the most expressed behaviour (Fetiveau *et al*., 2023b). Although in a prospective phase, the integration of rabbits and apple trees, in an agroforestry system (Savietto *et al*., 2023), seem to benefit both plants and animals (Savietto *et al*., 2024). Services of provision (such as food), regulation (disease control, herbivory, seed dispersal) and support (nutrient cycling, soil formation) naturally emerge in complex agroecosystems[1] integrating domestic plants, animals and wild life.

[1] "Agroecosystems are conceptual constructs, defined in both spatial and functional terms, that are used to describe parts of the biosphere managed primarily for the purpose of producing food, fibre and other agricultural products; they are made up of people, domesticated plants and animals, biotic and abiotic elements of the underlying soils and drainage networks, as well as interdigitating areas that support natural vegetation and wildlife. Agroecosystems exist because people create them to achieve nutritional and socioeconomic goals; they therefore have socioeconomic and public health, as well as environmental, dimensions" (Waltner-Toews, 1996).

MULTICRITERIA ANALYSIS

As early as 1987, the United Nations Brundtland Commission (https://www.un.org/en/academic-impact/sustainability) defined sustainability as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*". Put differently, sustainability is about the use of resources at a rate that is compatible to the replacement of the natural resources in use. In simple words, sustainability is about consumption and understanding that everything is connected: consumption needs products, products use resources and the use of resources impacts the environment. Because everything is connected, sustainability is about systematic thinking in a framework that values economy, equity and the environment in an interconnected and balanced way (https://www.sustain.ucla.edu/what-is-sustainability/).

In intertwined systems, a multicriteria analysis is necessary to assess the impact of a production on the three Es (economy, equity and environment). Fortun-Lamothe *et al*. (2009) and Theau-Clément *et al*. (2016) applied this method to evaluate different rabbit breeding practices. After discussing the limitations of the method applied to rabbit meat production, Fortun-Lamothe *et al*. (2009) found a positive result for the economic and social scales: total score of 1 out of 3 points, but a negative contribution to the environmental scale (minus 2 points) due to high use of energy, antibiotics and reduced biodiversity of the system.

Theau-Clément *et al*. (2016) compared three indoor rabbit rearing systems that differed mainly in their reproductive rhythm (intensive, semi-intensive and extensive). After assigning scores to 14 sustainability criteria (five for economic, five for equity and four for environmental), they found that the intensive and extensive systems changed the sustainability profile compared to the semi-intensive system in terms of the economic and equity criteria. The intensive system had a positive effect on two of the five economic criteria and a negative effect on the equity dimension, related to animal welfare, working conditions and product quality. In contrast, the extensive system had a positive effect on the economic criterion related to process efficiency and on the environmental criterion of biomass use.

A BRIEF DISCUSSION AND SOME PERSPECTIVES

This descriptive literature review presents some elements that allow us to quantify the main contributions of rabbit farming to global warming (greenhouse gas emissions), pollution (mostly nitrogen losses, airborne particulate matter), water footprint and biodiversity loss. As the majority of meat rabbits farmed in Europe (and in the world) are raised in indoor cage systems, the available studies only cover this production system. A single attempt has been made to quantify the environmental impact of an alternative system, based on rabbits grazing under photovoltaic panels (Pascaris *et al*., 2021). Although this study provides some insights into possible alternatives, the results obtained should be interpreted with caution as it is not based on real data.

Regarding the contribution of rabbit production to global warming, the estimations of greenhouse gas emissions ranged from 3.13 to 3.25 kg of CO_2 eq. per growing rabbit over a 35-d period (or from 3.78 to 4.04 kg of CO_2 eq. per kg of liveweight produced). Pollution associated with nitrogen losses varied between 40.1 and 59.1 g of N per kg of liveweight produced. Air pollution related to the airborne particulate matter (10 microns) varied from 0.082 to 0.045 mg per m^3, and there was no data available on the water footprint, which is likely to be between those observed for poultry and pig production. For biodiversity loss, there are no studies on the real impact of rabbit production on wildlife (plant and animals). As for greenhouse gas emissions, the latter may be attributed to the change in land use for crop farming, mainly soybean used for feed production. Wild rabbits, however, can be considered a keystone species of the Mediterranean scrubland.

In the current context, and this also applies to other livestock species, the "*long shadow*" of animal production is mainly related to the use of chemicals for crop production, to the change in land use to produce protein sources for animal feed (Cesari *et al*., 2018) and manure decomposition (Dinuccio *et al*., 2019; Hidayat *et al*., 2021). The studies carried out at the animal level (Estellés *et al*., 2009 and 2010; Franz *et al*., 2011) provide information on the real emissions from the normal metabolism of rabbits (growing animals only). Although this information is of great value, strategies aiming to reduce the greenhouse gas emissions directly related to the natural processes are limited (Monteny *et al*., 2006; Estellés *et al*., 2014; Biagini *et al*., 2021). Based on the digestive biology of rabbits, the reduced CH_4 emissions from their manure (Hidayat *et al.*, 2021) and the actual feeding practices (use of by-products, lucerne and feed restriction; Gidenne *et al.*, 2017), the environmental impact of rabbit meat production is expected to be lower than that from other livestock species.

The biological fact that living processes lead to the production of greenhouse gases raises the following question: Is life the problem? For some, yes. Animal production should be reduced (Willet *et al.*, 2019) to better feed the world and "*save the planet*". More extreme views argue for its abolition (Reese, 2018). For others, it is a question of spatial distribution. But there is no consensus on what should be done. Some will argue that the best policy is to intensify production to save land for nature; others will argue that sharing land with nature is the best option (Pearse, 2018). Maybe life is the only solution. But how can it be managed in a smart way that allows the production of high-quality food for all? For Kremen and Merenlender (2018), what is needed is an array of nature-friendly food production systems, created and managed in a way that is conducive to the emergence of ecosystem services, as experienced by Broom *et al.* (2013). This view is consistent with the concept of agroecosystems as defined by Conway in 1987: an ecosystem where productivity, stability, sustainability and equity are the key features.

For the rabbit sector (as it currently stands), the alternatives that have been tested in other livestock species, including the integration of crop and livestock, agroforestry and agroecology (Garrett *et al.*, 2020), may not be possible. The current socioeconomic and political context may limit the evolution of the current food production systems and the development of alternative models. In addition, the rabbit sector, at least in Europe, is facing a steady decline in demand. And this fact would certainly not help us to find alternatives if policies are not implemented to support the evolution required. But "*the show must go on*"!

Together with a team of agronomists, veterinarians, animal scientists and sociologists, we had the opportunity to design (Savietto *et al.*, 2023) and test (Savietto *et al.*, 2024) an alternative rabbit production system aiming at benefiting from the emergence of interspecific services combining rabbit and apple production. Although this experiment was a one-shot trial, the first results are promising. We were able to raise rabbits with less concentrated feed (about 28% less pellets compared to the indoor cage system and 5% less compared to a grassland system). In addition, at the end of a 35-d period, the fattened rabbits reached 2.7 kg at 80 days of age, with a reduced use of antibiotics (individual treatment) and only one death (out of 144 rabbits). Since 2021, our team has been producing reference values for pasture-based rabbit production systems, with technical results that are comparable to those of the indoor cage system (Fetiveau *et al.*, 2021; 2023a), not to mention the clear improvements in terms of animal welfare (Fetiveau *et al.*, 2023b, 2024). Other alternatives are also being tested by the French rabbit sector, as presented at the 12th World Rabbit Congress (Guené-Grand *et al.*, 2021).

Before being adopted, these alternatives should pass the scrutiny of rigorous scientific methods. The social acceptability of the proposed alternatives should also be assessed. But the declining demand for rabbit meat may not help. Despite these challenges, the rabbit sector should face the reality that rabbit farming may become a niche sector. In this sense, production methods that focus on sustainability and animal welfare should be strengthened.

At present, it is not possible to assess the environmental impact of alternative rabbit meat production systems. This is partly because they are still rare or experimental. Secondly, the reference methodologies used for assess greenhouse gas emissions may not be transferable, leading to biased estimates. The lack of harmonisation of current methodologies used to assess the environmental impacts of livestock production, at least for life cycle assessment methodologies (Goglio *et al.*, 2023), is an additional limitation.

In this context, the main perspectives of this descriptive review are: (i) in indoor systems, an accurate assessment of the contributions of rabbit meat production to global warming, water footprint, air pollution, land use change and biodiversity loss is needed; (ii) harmonisation of methods and units for reporting results is also needed to allow a direct comparison of the systems studied; (iii) for all the environmental impact parameters, results should be reported in terms of at least two main units, impact per kg of product and impact per area; (iv) impacts should be assessed considering all animal categories, in a whole system analysis; (v) universities, research institutions, farmers, cooperatives and agribusinesses should develop and evaluate alternative systems; (vi) the environmental impact of each alternative tested should be carefully evaluated; (vii) research programmes, and the credit and insurance systems should be redesigned; (viii) policies should be implemented to also pay for the ecosystem services provided by livestock farming and to safeguard food sovereignty and farmers' incomes.

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