Science of the Total Environment 737 (2020) 139702

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Effects of Dutch livestock production on human health and the environment

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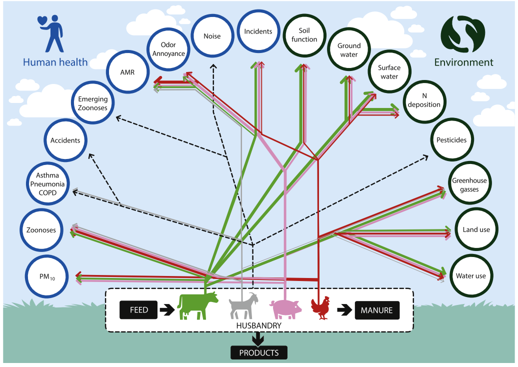
HIGHLIGHTS

- We assessed 17 human health and environmental impacts of Dutch livestock production.
- We used 8 actual Impact indicators, 6 State indicators and 8 Pressure indicators.
- Human health impacts ranged from beneficial to adverse effects.
- We assessed environmental impacts within and outside the Netherlands.
- Cattle, goat, pig and poultry sectors have distinctively different impact patterns.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 February 2020
Received in revised form 16 May 2020
Accepted 23 May 2020
Available online 28 May 2020

ABSTRACT

Observed multiple adverse effects of livestock production have led to increasing calls for more sustainable livestock production. Quantitative analysis of adverse effects, which can guide public debate and policy development in this area, is limited and generally scattered across environmental, human health, and other science domains. The aim of this study was to bring together and, where possible, quantify and aggregate the effects of national-scale livestock production on 17 impact categories, ranging from impacts of particulate matter, emerging

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Abbreviations: AMR, antimicrobial resistance; BoD, burden of disease; COPD, chronic obstructive pulmonary disease; DALY, disability-adjusted life year; $DDDA_{NAT}$, defined daily doses animal, national; DPSIR, drivers-pressures-state-impact-response; EIU, environmental indicator unit; ESBL, extended spectrum beta-lactamase; GHG, greenhouse gasses; NL, the Netherlands; PM, particulate matter; YLD, years lost due to disability; YLL, years of life lost.

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https://doi.org/10.1016/j.scitotenv.2020.139702

Editor: Jay Gan

Keywords:
Animal production
Livestock farming
Disability-adjusted life year (DALY)
Environmental impact
Climate impact

infectious diseases and odor annoyance to airborne nitrogen deposition on terrestrial nature areas and greenhouse gas emissions. Effects were estimated and scaled to total Dutch livestock production, with system boundaries including feed production, manure management and transport, but excluding slaughtering, retail and consumption. Effects were expressed using eight indicators that directly express Impact in the sense of the Drivers-Pressures-State-Impact-Response framework, while the remaining 14 express Pressures or States. Results show that livestock production may contribute both positively and negatively to human health with a human disease burden (expressed in disability-adjusted life years) of up to 4% for three different health effects: those related to particulate matter, zoonoses, and occupational accidents. The contribution to environmental impact ranges from 2% for consumptive water use in the Netherlands to 95% for phosphorus transfer to soils, and extends beyond Dutch borders. While some aggregation across impact categories was possible, notably for burden of disease estimates, further aggregation of disparate indicators would require normative value judgement. Despite difficulty of aggregation, the assessment shows that impacts receive a different contribution of different animal sectors. While some of our results are country-specific, the overall approach is generic and can be adapted and tuned according to specific contexts and information needs in other regions, to allow informed decision making across a broad range of impact categories.

1. Introduction

Livestock production imposes several environmental and public health effects. At the global level, livestock production contributes to greenhouse gas emissions (Gerber et al., 2013; Herrero et al., 2011); overuse of finite resources such as land, water, and phosphorus (Herrero et al., 2015; Leip et al., 2015); the development of antimicrobial resistance (Chantziaras et al., 2014; Marshall and Levy, 2011; Silbergeld et al., 2008); and the threat of emerging diseases, such as pandemic influenza (FAO, 2013; Jones et al., 2013; WHO, 2017b). Locally, livestock production contributes to nutrient surpluses affecting soil and water quality (Oenema et al., 2007; Sutton et al., 2011); ecotoxicological effects of pesticide application (Nordborg et al., 2017); odor annoyance (Hooiveld et al., 2015); and human health effects from exposure to particulate matter, endotoxins and pathogens (Casey et al., 2015; Douglas et al., 2018; Smit and Heederik, 2017). In addition, there are safety concerns regarding occupational hazards associated with livestock production (Berkhout et al., 2015) and regarding explosions and biogas leaks in manure fermentation systems (Dutch safety board, 2014; Dutch safety board, 2016).

Many of these concerns are especially relevant in areas with large animal and human population densities, found in countries such as the Netherlands, Belgium, Denmark, France, Germany, the USA, and China (Robinson et al., 2011). The Netherlands (41.543 km^2 total area, including water bodies) was chosen as a case region with average densities of 14 goats, 93 cattle, 298 pigs and 2372 poultry per km^2 and of 414 persons per km^2 in 2018 (CBS, 2019a). Over the past decade the public debate about livestock production and consumption intensified in the Netherlands (Kraaij-Dirkzwager et al., 2017), with the globally recognized Q-fever epidemic of 2007–2010 occurring in one of the country's most densely populated livestock areas (Roest et al., 2011). Public awareness appears also fueled by other infectious disease outbreaks, such as mad cow disease (BSE) in Europe in the early 1990s, classical swine fever in the Netherlands in 1997–1998, foot-and-mouth disease in the UK and in the Netherlands in 2001 and the global threat of avian influenza since the late 1990s (Mangen and Burrell, 2001; OIE, 2016). Other developments that may have sharpened the public debate include the Paris Agreement to tackle climate change (Klimaatberaad, 2019; United Nations, 2015a), and national policy programs to stop the decline in biodiversity such as the Integrated Approach to Nitrogen (PAS). The latter agreement was a national policy superimposed on the Dutch implementation of the European Habitat Directive and recently led to renewed debate about measures to cut emissions of nitrogen oxides and ammonia when the Dutch Council of State judged that the approach was not compliant with the European directive. The greater attention on sustainable livestock production in the Netherlands is reflected in the initiation of large studies on the human health effects related to living in the vicinity of livestock farms (Heederik and Yzermans, 2011; Maassen et al., 2016) and the formulation of 15 ambitions around a shift toward more sustainable livestock production by multiple Dutch governmental and non-governmental actors (Bos et al., 2017; UDV, 2013). More recently, several policy-oriented publications have called for a new, sustainable orientation to intensive animal husbandry (Ministry of Agriculture, 2018; RLI, 2018; SER, 2016; Vink and Boezeman, 2018).

The public debate on the future of livestock production systems could benefit from an evidence-based overview of the environmental and human health effects of livestock production. Knowledge about such effects, however, is scattered across research domains, and have so far been assessed together to only a limited extent (Aequator Groen en Ruimte et al., 2008; Boone and Dolman, 2010; Bos et al., 2017; Hu et al., 2017; Westhoek et al., 2011). A simultaneous rather than separate assessment of environmental and human health impacts may provide more thorough insight into the challenges that arise when responding to them. The importance of such an integrated approach becomes clear in the example of the historic ban on battery cages for laying hens, with the focus on animal welfare, but concurrent increases in particulate matter emissions, nitrogen emissions, and carbon emissions (Dekker et al., 2011; Takai et al., 1998; Winkel et al., 2016). Another example is the increase in the number of goat farms, which appears to have been driven by introduction of the European milk quotation system for dairy cattle farmers in 1984, as well as by the classical swine fever and foot-and-mouth disease outbreaks of the 1990s and earlier 2000s. The resulting 50-fold increase of goat farms between 1983 and 2009 in turn contributed to the Q-fever epidemic in the Netherlands between 2007 and 2010, mirroring situations in Bulgaria and Canada: an increase in dairy goat farming appears to have driven Q-fever outbreaks there as well (Hatchette et al., 2001; Roest et al., 2011). A broad assessment may thus offer insight into both the variety of responses that are required, and the possible unintended consequences and trade-offs of such responses in relation to other impacts.

The main aim of this study therefore was to assess the multiple human health and environmental impacts of Dutch livestock production, and assess differences between animal sectors.

2. Methods

2.1. General approach

We cover 17 different themes in the human health and environmental domains, associated with livestock production that we refer to as *impact categories*. The selected impact categories have been extensively studied, have been recognized as sources of particular concern by citizens, or are already subject of regular monitoring (Table 1). For each

Table 1
Domains, impact categories and indicators for analysis of human health and environmental impacts of Dutch livestock production, representing impacts or proxies of impacts (according to the DPSIR causal chain).

Domain	#	Impact category	Indicator (unit)	PSI[a]
Human Health	1	Particulate Matter	Burden of disease (BoD[b]) related to particulate matter emissions from livestock production, expressed as disability-adjusted life years (DALY[c])	I
	2	Zoonoses	BoD related to livestock-related zoonoses transmitted through direct contact with livestock or through indirect transmission via the environment (DALY)	I
	3	Pneumonia, asthma and COPD[d]	BoD related to pneumonia, asthma and COPD among residents living in the vicinity of livestock farms (DALY)	I
	4	Accidents	BoD related to occupational accidents in the livestock sector (DALY)	I
	5	Emerging zoonotic disease risks	Impact and probability of an emerging zoonotic disease (descriptive)	I
	6	Antimicrobial resistance		
		a. ESBL/pAmpC source attribution	Persons carrying Beta-Lactamase-producing (ESBL/pAmpC) *E. coli* attributed to direct contact or environmental transmission from animal husbandry (%)	S
		b. Antimicrobial use	Use of antimicrobials in livestock ($DDDA_{NAT}$[e])	P
	7	Odor annoyance	Persons severely annoyed by odors from livestock production processes (%)	I
	8	Noise	Persons severely annoyed by noise from livestock production processes (%)	I
	9	Incidents manure fermentation systems	Buildings within a safety distance of 30 m from a manure fermentation system (number)	P
Environment	10[f]	Nutrient-related impacts on soil functioning		
		a. Nitrogen transfer	Transfer of nitrogen to soil related to livestock production (tonnes per year)	P
		b. Phosphorus transfer	Transfer of phosphorus to soil related to livestock production (tonnes per year)	P
		c. Phosphorus saturation	Level of P saturation expressed as share of the P saturated area over the total available area for agriculture at the level of a farm or region (%).	S
		d. Relative crop and grass production area	Percentage of area for crop production in total area for livestock feed production (%)	P
	11[f]	Nitrate pollution of groundwater	Average nitrate concentration in the shallow groundwater layer under agricultural land (mg/L as NO_3^- per region)	S
	12[f]	Surface water eutrophication		
		a. chemical water quality standard exceedance	Percentage of agricultural water bodies exceeding nutrient standards for N and P (%)	S
		b. biological water quality standard exceedance	Percentage of regional water bodies with insufficient biological water quality (in one of lowest 3/5 classes; %)	S
	13	Nitrogen deposition in terrestrial nature	Percentage of nature areas in which the critical loads are exceeded (% of surface area)	S
	14	Environmental impacts of pesticides application	Environmental impact related to pesticide use for livestock feed production in the Netherlands (Environmental Indicator Units: EIUs)	I
	15	Greenhouse gas emissions	Greenhouse gas emissions from production processes related to livestock production (kg CO_2-equivalents)	P
	16	Land use	Agricultural land use area required for livestock-feed production for livestock production (km^2)	P
	17	Water use	Blue water required for production processes related to livestock production (m^3)	P

[a] PSI: P = Pressure, S = State, I = Impact.
[b] BoD: burden of disease.
[c] DALY: disability-adjusted life year.
[d] COPD: chronic obstructive pulmonary disease.
[e] $DDDA_{NAT}$: defined daily doses animal, national.
[f] Overlap in impact.

impact category, we selected one or a set of indicators, using the Driver-Pressure-State-Impact-Response (DPSIR) framework (EEA, 2005; Smeets and Weterings, 1999) as a useful conceptual 'Level 2 Relational framework' (Knol et al., 2010), with a focus on P-S-I indicators and preference for indicators representing an Impact (the D for Driving Force and R for Response from DPSIR are outside the scope of this study). The ability to link the indicator to livestock production was another important selection criterium for indicators. Other criteria that were adopted for selecting indicators, corresponding to guidelines for selecting and developing indicators (Corvalán et al., 1996; Harger and Meyer, 1996; Niemeijer and de Groot, 2008) were availability of data, interpretability, sensitivity to changes over time, validity with respect to the representation of the impact category, objectivity, and specificity. Each indicator provides a proxy or direct indication for the impact of the entire Dutch livestock production within a specific impact category and is quantitative where possible. When (data on) suitable Impact indicators were not available, selected indicators are a more indirect indication of Impact by expressing a Pressure (such as greenhouse gas emissions) or a State (such as nutrient concentration; Table 1). Such Pressure and State indicators were mostly used in the environmental domain, thereby in some cases relating both to ecosystem integrity and human health, whereas for the human health domain, mostly Impact indicators were used.

Aggregation and integration of different indicators were performed only to the extent that the resulting sets of indicators were still practical, meaningful and in line with the meaning in the relevant knowledge domains. To facilitate interpreting the indicator estimates, we compare them, where possible, to a value for comparison. These values for comparison are either the total impact related to all sources (e.g., total burden of disease related to particulate matter emissions) or other sources of impact or data that provide a context for the estimate (e.g., odor annoyance related to livestock production is compared to odor annoyance related to sewage systems).

To allow impact estimation, we defined system boundaries, which included feed production both within and outside the Netherlands, manure management and transport, but excluded slaughtering, retail, and consumption. Transboundary effects were assessed only for impact categories concerning resource use and for greenhouse-gas (GHG) emissions, for which data were sufficiently available. Data used to quantify indicators were retrieved directly from the literature or existing databases, or calculated specifically for this study. In principle, data from 2015 were used to quantify indicators. When data from 2015 were not available, data for years closest to 2015 were used. In the absence of suitable quantitative data, a qualitative, more narrative approach was adopted. Wherever possible and appropriate, estimates were derived across different animal categories, impact sources, diseases, or regions. The methods used to provide estimates for each indicator are described briefly below and in more detail in the Supplement (Supp1–17). The latter also includes a description of the main sources of uncertainty for each indicator.

2.2. Human health indicators

A common Impact indicator to express the burden of disease (BoD) from mortality and morbidity is the disability-adjusted life year (DALY). This metric consists of the total estimated years of life lost (YLL) due to premature death and the years of life lived with disability (YLD), calculated separately across diseases (Gold et al., 2002; Murray and Lopez, 1997; Murray et al., 2012). The DALY indicator was used in this study to express the BoD related to *particulate matter, zoonoses, pneumonia, asthma, COPD* and *accidents.*

The BoD associated with *particulate matter* emissions was estimated by first calculating the population-averaged exposure to livestock-related particulate matter (PM) based on an atmospheric dispersion model (Sauter et al., 2018). This particulate matter includes both a primary and a secondary fraction. Primary PM is dust emitted directly from animal production facilities and can affect nearby communities. Secondary PM originates from reactions of ammonia (NH_3), nitrogen oxides (NO_x) and sulfur dioxide (SO_2) in the atmosphere and can affect communities over greater distances. The numbers of deaths and cases of respiratory and cardiovascular diseases attributable to livestock-related PM_{10} exposure for five-year age-groups were estimated based on published relations between PM_{10} exposure and mortality and morbidity. From these numbers, the BoD expressed as DALYs was calculated, using age-group-specific life expectancy to calculate YLL and using YLD estimates per case for non-fatal diseases (Supp1). The BoD associated with livestock-related *zoonoses* (i.e., infectious diseases infecting both animals and humans), was limited to those transmitted either by direct livestock animal contacts or indirect transmission via the environment. The associated BoD estimates, expressed as DALYs, were based on the total BoD estimates for all relevant pathogens from several data sources, and on the attributable fractions per animal and per transmission route, using expert elicitation (Supp2). These estimates do not include the potential future BoD of emerging zoonoses or incremental BoD due to antibiotic resistance. DALYs for *pneumonia, asthma, and COPD* due to living in close proximity to livestock farms were estimated using the same approach as for the BoD associated with particulate matter. These BoDs were estimated by first calculating the number of persons living within specific distances of livestock farms, and subsequently using odds-ratios from several studies to estimate attributive cases and calculating DALYs based on these cases (Supp3). The BoD associated with *accidents* involving persons working in the livestock sector was estimated based on the number of notified cases among employees, whereby distinguishing between fatal cases for estimating YLLs, and non-fatal cases with either permanent or non-permanent lesion for estimating YLDs. The BoD for employees was extrapolated to the total population of persons working in the livestock sector by assuming that the rate of accidents is similar among employers and employees (Supp4).

The DALY metric is not suitable for all impact categories selected here. For example, because they concern impacts that have a low probability of occurrence (less than once every few years), but a potentially high impact (e.g. a Q fever outbreak), or because the health effects involved are not considered as a diagnosable 'disease' per se in the medical community, e.g. carriership of antimicrobial resistance (from antibiotic use), hypertension (from noise exposures), or for odor annoyance. While in some cases, 'translation' to a DALY is in principle possible, the results would lose meaning to the public health community as well is to the societal and political debate. The potential Impact for *emerging zoonotic disease risk* is expressed in two separate metrics, i.e. the probability and the potential impact of an outbreak of a specific zoonotic disease. These have been determined based on expert judgement, in the context of several other potential future risks in the national security profile (Analistennetwerk Nationale Veiligheid, 2016; Supp5). The Impact of *antimicrobial use* in livestock production and the potential incremental BoD associated with antimicrobial resistant infection is currently hard to quantify. As an example, the attribution of Extended Spectrum Beta-Lactamases (ESBLs) to animal husbandry based on the results of the ESBLAT study (Mevius et al., 2018) and related work (Mughini-Gras et al., 2019) is presented here as State indicator, i.e. prevalence of carriership. In addition, the current use of antimicrobials in livestock is presented as a Pressure indicator (SDa, 2017; Veldman et al., 2016; Supp6). *Odor and noise annoyance* were expressed as Impact indicators in terms of the percentage of severely annoyed persons based on several surveys (Supp7, Supp8). The potential health Impact of *incidents with manure fermentation systems*, such as explosions and leaks of toxic gasses, was expressed as a Pressure indicator: the number of homes in the proximity of such systems (Supp9), which is generally used as a safety measure in the process of issuing building permits for such systems.

2.3. Environmental indicators

Some of the chosen environmental indicators only concern the impacts that occur within the Netherlands. Other indicators concern impacts that occur both in the Netherlands and abroad. We distinguish these here as national environmental indicators and global environmental indicators.

2.3.1. National environmental indicators

The effect of livestock production on national environmental impacts was specified for four environmental compartments: agricultural soils, groundwater, surface water and terrestrial nature. We distinguished four nutrient-related impact categories (Table 1: 10–13), and one impact category that addresses the effects of pesticides on groundwater and surface water compartments (Table 1: 14). The indicators used to quantify each impact category are presented below.

Four indicators were selected to quantify *nutrient-related impacts on soil functioning*, where soil functioning refers to the ability of soils to provide a range of soil functions, including primary production, carbon sequestration, nutrient retention, water retention and natural attenuation. The first two indicators are the total transfer of nitrogen and phosphorus to soils, related to livestock production. These Pressure indicators are derived from national nutrient budgets, as published by Statistics Netherlands (CBS, 2019b; Supp10a,b), which include input of nutrients, in the form of artificial fertilizer and natural deposition, and outputs in the form of crop-harvest and flows of nutrients to the environment. These budgets contain information on several input sources and output fates, allowing the attribution of nutrient flows to soils and any subsequent flows to groundwater and surface waters (impact categories 11 and 12), to livestock production. The third indicator for *nutrient-related impacts on soil functioning* is the State of phosphorus saturation, based on soil measurements (CBS et al., 2008; Supp10c). The fourth is the percentage of maize land in the total area of feed production (maize + grass) reflecting a Pressure on the ability of soils to retain nutrients (Supp10d).

The second national environmental impact category is *nitrate pollution of groundwater* and is quantified as nitrate concentration in groundwater under agricultural fields (i.e. mg NO_3^-/L). This State indicator is quantified using measurements of water that leaches from the rootzone of a sample of representative farms in sandy soil, clay, loess, and peat regions in the Netherlands between 2012 and 2015 (Supp11). The percentage of farms at which the acceptable limit of50 mg NO_3^-/L (European Commission, 1991) is exceeded is presented. The contribution of livestock production to the nitrate concentration, relative to other contributing sources, could not be precisely determined based on readily available data, but to provide some insight in this contribution, estimates specifically for dairy farms are reported in addition to estimates for all (also non-livestock) farms (Supp11).

The third national environmental impact category describes the effects of nutrient transfers on *surface water eutrophication*, and is quantified using two State indicators. The first is the percentage of agricultural water bodies exceeding waterbody-specific water quality standards for nitrogen and phosphorus. The second is the percentage of regional water bodies exceeding ecological standards, based on samples taken in several representative water bodies (Klein and Rozemeijer, 2015; van Grinsven et al., 2017; Supp12). The contribution of livestock production to the percentage of agricultural water bodies exceeding water quality standards could not specifically be determined. The contribution of livestock production to the water quality of regional waters is determined based on a modelling study (Groenendijk et al., 2016; Supp 12).

Another national environmental impact category is the *nitrogen deposition on nature areas*, which entails direct nitrogen deposition from the air. Nitrogen deposition was determined using a combination of modelled data and measurements and was subsequently compared to critical loads (deposition loads below which no observable effects on biodiversity occur) to obtain exceedances of the critical loads (Supp13). To assess the contribution of livestock production to such deposition, we present model results of nitrogen deposition with and without emissions from animal husbandry.

A final national environmental impact category is the *environmental impacts of pesticide application* on maize and grass, which represent the most important agricultural land uses for livestock production in the Netherlands. The indicator used to quantify this Impact is Environmental Indicator Units, which indicate the pesticide concentrations in several environmental compartments relative to reference values; legal maximum permissible concentrations for chronic effects on water organisms for the surface water compartment, and a drinking water quality criterion for the groundwater compartment (Verschoor et al., 2019; Supp14).

2.3.2. Global environmental indicators

For the impact categories *greenhouse gas emissions*, *land use,* and *water use,* we were able to make a global estimate and a national estimate of Pressures. The global estimate concerns processes related to the entire life cycle, including, for example, production processes abroad for the production of livestock feed that is consumed by Dutch livestock. For this global estimate, we first determined the total amount of livestock products produced in the Netherlands using several data sources (Appendix of Supplement). Subsequently, we multiplied these production volumes with the greenhouse gas emissions, land use, and blue water use related to single products, derived from the Agri-footprint database (Duringer et al., 2017; Supp15–17). These estimates are complemented by national estimates, concerning greenhouse gas emissions, land use, and water use within the Netherlands. Estimates of livestock-related greenhouse gas emissions within the Netherlands were based on the National Emission Inventory (Coenen et al., 2018; Supp15). Estimates for land use in the Netherlands were based on agricultural land used for livestock feed production (Supp16). Estimates of water use for livestock production in the Netherlands were based on van der Meer (2018; Supp17).

3. Results

Estimates for all 17 impact categories (Table 1) are expressed in eight Impact, six State and eight Pressure indicators and presented in Tables 2-5. Where possible, these are broken down by different animal sectors and compared to values for comparison. We present a summary of the overall impact in the table, followed by an explanation for each impact category.

3.1. Burden of disease estimates

The four human health impacts that could be expressed in Impact indicators for burden of disease (BoD), i.e. in disability-adjusted life years (DALYs) are presented in Table 2 and include both estimated beneficial and adverse effects on human health. The beneficial effects pertain to asthma and COPD in association with living close to livestock farms. The specific mechanisms underlying these associations are not fully understood, yet a lower prevalence of atopic asthma and allergies has been frequently observed in children and adults that have lived in farming areas and finds some biological plausibility in the “hygiene-hypothesis” (Borlée et al., 2015; Ege et al., 2011; Kauffmann et al., 2002; Riedler et al., 2001; Smit et al., 2014; von Mutius, 2016; von Mutius and Vercelli, 2010). Although direct comparison is not straightforward due to methodological differences, under the current assumptions, the estimated beneficial effects appear similar in magnitude to the estimated burden from adverse effects.

3.1.1. Impact category 1: particulate matter

The population-averaged concentration of particulate matter that is smaller than 10 μm in diameter (PM$_{10}$) that can be attributed to Dutch livestock production was 0.75 μg/m^3 in 2015, which is about 4% of the total population-averaged PM$_{10}$ concentration from all sources (Supp1). Exposure to PM causes premature mortality and several respiratory and cardiovascular diseases (Supp1). Assuming the same relation

Table 2

Point estimates of indicators for selected livestock-related human health impact categories that could be expressed in DALYs.[a]

Impact category	Indicator[b]	Estimate[c]	Comparison[d]	Cattle[e]	S Rum[e]	Pigs[e]	Poultry[e]
1. Particulate Matter	Burden of disease (I)	6,300 DALYs per year	4% of total DALYs related to air pollution	31%		19%	30%
Primary[f]		*28 %*		*2%*		*5%*	*21%*
Secondary[f]		*72 %*		*30%*		*14%*	*9%*
2. Zoonoses	Burden of disease (I)	2400 DALYs per year	4% of a total of 38 infectious diseases	23%	4%	20%	53%
3. Pneumonia, asthma and COPD	Burden of disease (I)	Pneumonia: 300 DALYs per year	1% of total LRI[h] DALYs		100%		
		COPD: −10,000 DALYs per year[g]	5% of total COPD DALYs	*Not attributed*			
		Asthma: −600 DALYs per year[g]	2% of total asthma DALYs				
		COPD exacerbations: 1500 DALYs per year					
4. Accidents	Burden of disease (I)	300 DALYs per year	4% of total occupational accident DALYs	*No data available*			

[a] A more comprehensive description of indicators can be found in Table 1 and more information on their calculation and sources of uncertainty are presented in the Supplement.

[b] A more comprehensive description of the indicator can be found in Table 1 and in the Supplement; I refers to Impact indicator.

[c] Trailing zeros do not represent significant numbers; hence DALY estimates have either 1 or 2 significant numbers.

[d] Value for comparison to provide context for the estimate in the light of other sources of impact or other comparisons, see text and Supplement for background.

[e] S Rum = Small Ruminants; When contributions of animal sectors do not add up to 100%, part of the impact cannot be attributed to a specific animal sector (see Supplement). Cattle includes dairy cattle and beef cattle. Poultry includes laying hens, broilers, and other poultry.

[f] Primary particulate matter is directly emitted from livestock farms. Secondary particulate matter originates from reactions of substances in the atmosphere, i.e. from ammonia emissions originating from livestock farms (see Supplement).

[g] A negative burden represents a beneficial effect.

[h] Lower Respiratory tract Infections.

between morbidity and mortality of livestock-related PM, compared to other PM sources, leads to an estimated burden of disease of about 6300 DALYs (Table 2). The main contributors to this BoD are primary PM emissions from poultry farms and secondary PM related to ammonia emissions from cattle farms, whereas primary PM emissions from cattle farms contribute relatively little (Table 2). The primary PM emissions lead to peak PM_{10} levels in the vicinity of poultry farms, as indicated by higher concentrations in livestock-dense provinces. The secondary PM_{10} fraction shows a more wide spread pattern contributing more equally to the exposure of the population across the Netherlands (Supp1).

3.1.2. Impact category 2: zoonoses

The BoD related to direct animal contact and indirect transmission via the environment is estimated at 2400 DALYs in 2016 (Table 2; Supp2). This is about 4% of the total burden of 38 communicable diseases (including Influenza and i. pneumococcal disease) in the Netherlands and about 36% of the total BoD of the considered zoonoses, which are for a large part transmitted via the food-transmission route, which are outside our specified system boundaries (Supp2). The highest contributions to this BoD come from poultry (53%) and cattle (23%, Table 2) and can be largely attributed to *Campylobacter* spp. The contribution of pigs (20%, Table 2) is mainly attributed to Hepatitis E virus and non-typhoidal *Salmonella* spp. (Supp2).

3.1.3. Impact category 3: pneumonia, asthma and COPD

Recent studies have shown an increased risk of pneumonia among residents living within up to 2000 m from goat farms (Freidl et al., 2017; Kalkowska et al., 2018; Post et al., 2019). In addition, a decreased prevalence of asthma and COPD has been reported among residents living within 500 m of livestock farms (Borlée et al., 2015; Smit et al., 2014). At the same time, among the persons that do live in the vicinity of livestock farms and do have COPD, disease exacerbation is thought to be more frequent (Borlée et al., 2015; van Dijk et al., 2016). Mechanisms underlying most of these associations are only limitedly understood, yet if associations would be causal, the number of persons affected could be high as about 87% of Dutch residents lives within 2000 m and about 21% within 500 m from a livestock farm (Fig. 1; Supp3). Under the assumption of causality, disease burden due to pneumonia and the increased burden of exacerbations are weighted against fewer COPD and asthma cases, and hence the overall health effect would be beneficial, and would equal about 9000 DALYs (Table 2).

3.1.4. Impact category 4: accidents

Occupational accidents in the livestock sector are estimated to account for 280 DALYs per year (average over 1999–2013), which can mainly be attributed to lethal accidents (Supp4). This is about 4% of the total burden of occupational accidents in the Netherlands (Table 2; Supp4). The average number of accidents in the agricultural sector is 85 per 100.000 work years, which makes agriculture the sector with the third most frequent accidents and is higher than the average of 28 per 100.000 work years (Inspectie SZW, 2018). The estimate cannot be further specified to the level of animal sectors based on the available data.

3.2. Other human health impacts

The estimates for five human health impact categories for which the Impact could not be expressed in DALYs are presented in Table 3. For these impact categories, BoD estimates are not appropriate, e.g. because of 'low probability of occurrence with uncertain impact', or because the effect on health is not considered a 'disease' per se. The estimates include

Table 3

Point estimates of indicators for selected livestock-related human health impact categories for which the impact could not be expressed in DALYs.[a]

Impact category	Indicator[b]	Estimate	Comparison[c]	Cattle[d]	S Rum[d]	Pigs[d]	Poultry[d]
5. Emerging zoonoses	Probability	Somewhat probable	0.5–5% probable, no actual indications; imaginable	*No attribution possible*			
	Potential impact (I)	Severe	Several hundreds of deaths, >4000 severe illnesses				
6. Antimicrobial resistance							
a. ESBL attribution	Persons with livestock-attributable ESBL/pAmpCs (S)	6% of 5% ESBL/pAmpC carriers	Person to person: 67% Foodborne: 19%	27%	4%	7%	61%
b. Antimicrobial use	Use of antimicrobials in livestock (P)	Broilers: 9.4 $DDDA_{NAT}$ in 2015	27.4 $DDDA_{NAT}$ reduction since 2009				
		Pigs: 8.7 $DDDA_{NAT}$ in 2015	11.8 $DDDA_{NAT}$ reduction since 2009				
		Dairy cattle: 3.1 $DDDA_{NAT}$ in 2015	2.7 $DDDA_{NAT}$ reduction since 2009				
		Veal calves: 20.1 $DDDA_{NAT}$ in 2015	13.7 $DDDA_{NAT}$ reduction since 2009[e]				
7. Odor annoyance	Percentage of persons reporting severe annoyance (I)	< 2.5% of all Dutch inhabitants and up to 8% in some municipalities in the south-east of the Netherlands	Industry: 1.3% Sewage: 2.4%	20%	?	80%	40%
8. Noise	Percentage of persons reporting severe annoyance (I)	*Unknown*	Road traffic: 9.3% Air planes: 2.6%	*No data available*			
9. Incidents manure fermentation systems	Homes within 30 m (P)	100 homes	*Not applicable*	40%[f]		55%[f]	1%[f]

[a] A more comprehensive description of indicators can be found in Table 1 and more information on their calculation and sources of uncertainty are presented in the Supplement.

[b] A more comprehensive description of the indicator can be found in Table 1 and in the Supplement; P, S and I respectively refer to Pressure, State and Impact indicators.

[c] Value for comparison to provide context for the estimate in the light of other sources of impact or other comparisons (see text and Supplement for background).

[d] S Rum = Small ruminants. When contributions of animal sectors do not add up to 100%, part of the impact cannot be attributed to a specific animal sector (see Supplement). Cattle includes dairy cattle and beef cattle. Poultry includes laying hens, broilers and other poultry.

[e] Decrease in antimicrobial use between 2009 and 2014 led to a decrease of 8–79% of AMR in animals, indirectly leading to less human resistance, particularly in farmers (see text and Supplement).

[f] Based on contribution to manure processed in manure fermentation systems (see Supplement).

Table 4
Point estimates of indicators for selected livestock-related impact categories concerning national environmental impacts.[a]

Impact category	Indicator[b]	Estimate	Comparison[c]	Cattle[d]	S Rum[d]	Pigs[d]	Poultry[d]
10. Nutrient-related impacts on soil functioning	Nitrogen transfer (P)	225×10^6 kg N year^{-1}	66% of total N transfer	64%		20%	12%
	Phosphorus transfer (P)	7.8×10^6 kg P year^{-1}	95% of total P transfer	57%		22%	15%
	Phosphorus saturation (S)	56%					
	Percentage crop-land (P)	30%	max. 20% for derogation[e]				
11. Nitrate pollution of groundwater	Average nitrate concentration (S)	Sand-region: 55 mg/L	47% exceedance of 50 mg/L	*No attribution possible*			
		Clay-region: 20 mg/L	8% exceedance of 50 mg/L				
		Loess-region: 69 mg/L	60% exceedance of 50 mg/L				
		Peat-region: 8 mg/L	0% exceedance of 50 mg/L				
12. Surface water eutrophication	Chemical water quality standard exceedance (S)	Sand-region: N 50–70%; P 38–54%		*No attribution possible*			
		Clay-region: N 43–58%; P 37–48%					
		Peat-region: N 50–80%; P 58–92%					
	Biological water quality standards exceedance (S)	95%					
13. Nitrogen deposition in terrestrial nature	Nature areas with excess nitrogen deposition (S)	45% of the surface area in all nature areas is exceeded due to livestock production	75% of the exceeded surface area of all nature areas	63%		21%	11%
14. Environmental impacts of pesticide application	Environmental Indicator Units (EIUs) (I)	Groundwater: 902 EIUs/ha	104% of total EIUs/ha in agriculture	*No attribution possible*			
		Surface water: 0.9 EIUs/ha	5% of total EIUs/ha in agriculture				

[a] A more comprehensive description of indicators can be found in Table 1 and more information on their calculation and sources of uncertainty are presented in the Supplement.
[b] A more comprehensive description of the indicator can be found in Table 1 and in the Supplement; P, S and I respectively refer to Pressure, State and Impact indicators.
[c] Value for comparison to provide context for the estimate in the light of other sources of impact or other comparisons, see text and Supplement for background.
[d] S Rum = Small ruminants. When contributions of animal sectors do not add up to 100%, part of the impact cannot be attributed to a specific animal sector (see Supplement). Cattle includes dairy cattle and beef cattle. Poultry includes laying hens, broilers and other poultry.
[e] The derogation allows farmers to apply more nitrogen in the form of ruminant manure than is normally allowed under the European Nitrates directive, if they fulfill certain requirements.

(1) a somewhat probable emerging infectious disease outbreak with a severe impact; (2) an attribution of ESBL/pAmpc antimicrobial resistance to livestock farming of about 6% and markers of use of antimicrobials in livestock that has reduced in all animal sectors since 2009; (3) a percentage of Dutch inhabitants severely annoyed by odors from livestock production processes of <2.5%; (4) an unknown percentage of persons severely annoyed by noise related to livestock production processes; (5) and 100 homes within 30 m of a manure fermentation system.

3.2.1. Impact category 5: emerging zoonotic disease risk

Besides zoonoses that are currently seen (described above), new zoonoses may emerge and existing zoonoses may flare up (re-emerge) when pathogens appear in a new host, evolve novel traits or settle in a new area (Engering et al., 2013). An example of such a re-emerging zoonosis is Q-fever, which was low-endemic in the Netherlands for a long period (20 cases reported/annum) before it caused a major epidemic among persons living up to 5 km from goat farms (De Rooij et al., 2019; van der Hoek et al., 2011), resulting in >4000 notified cases in 2007–2010 and 95 officially estimated deaths as of 2019. Although factors contributing to emerging zoonoses, such as the increase in farm animal populations, have been identified (Engering et al., 2013; Liverani et al., 2013; Mori and Roest, 2018), predicting or modelling zoonosis emergence remains difficult.

Despite the difficulties inherent in predicting emerging zoonotic disease outbreaks, a qualitative indication of emerging zoonotic disease risk has been provided in the national security profile of the Netherlands (Analistennetwerk Nationale Veiligheid, 2016), in which potential national disasters, crises, or threats are identified, and their probability and impact are described in qualitative terms. An example is avian influenza, of which the occurrence of an outbreak in the next 5 years has been judged as somewhat probable and the impact as severe, leading to severe infections and deaths, entailing costs and affecting the accessibility of certain areas, daily life and the societal debate (Table 3; Supp5; Analistennetwerk Nationale Veiligheid, 2016). However, inferring from such example the pressure of different animal sectors on zoonotic disease emergence is impossible. Better insight into factors driving pathogen emergence and disease-specific knowledge such as the reservoir, pathogen prevalence and traits, and human exposure and internal barriers is required (Engering et al., 2013; Plowright et al., 2017).

3.2.2. Impact category 6: antimicrobial resistance

There is increasing evidence for an association between antibiotic use in livestock and antimicrobial resistance (AMR) in humans (Supp6), even as the attribution of AMR in humans to different sources, such as proximity to or contact with farm animals, is methodologically very challenging. According to recent estimates based on an extensive national project, about 6% of the carriage of Extended Spectrum Beta-

Table 5
Point estimates of indicators for selected livestock-related impact categories concerning global environmental impacts.[a]

Impact category	Indicator[b]	Estimate	Comparison[c]	Cattle[d]	S Rum[d]	Pigs[d]	Poultry[d]
15. Greenhouse gas emissions	Greenhouse gas emissions (P)	Global: 42×10^9 kg CO_2-eq.		62%	1%	22%	15%
		NL: 18×10^9 kg CO_2-eq	9% of total emissions occurring in NL				
16. Land use	Area (P)	Global: 26×10^3 km^2		44%	1%	34%	21%
		NL: 14×10^3 km^2	70% of Dutch agricultural land use				
17. Water use	Blue water use (P)	Global: 28×10^7 m^3		54%	1%	20%	25%
		NL: 1×10^8 m^3	2% of Dutch water use				

[a] A more comprehensive description of indicators can be found in Table 1 and more information on their calculation and sources of uncertainty are presented in the Supplement.
[b] A more comprehensive description of the indicator can be found in Table 1 and in the Supplement; P refers to Pressure indicator.
[c] Value for comparison to provide context for the estimate in the light of other sources of impact or other comparisons (see text and Supplement for background).
[d] S Rum = Small ruminants. When contributions of animal sectors do not add up to 100%, part of the impact cannot be attributed to a specific animal sector (see Supplement). Cattle includes dairy cattle and beef cattle. Poultry includes laying hens, broilers and other poultry.

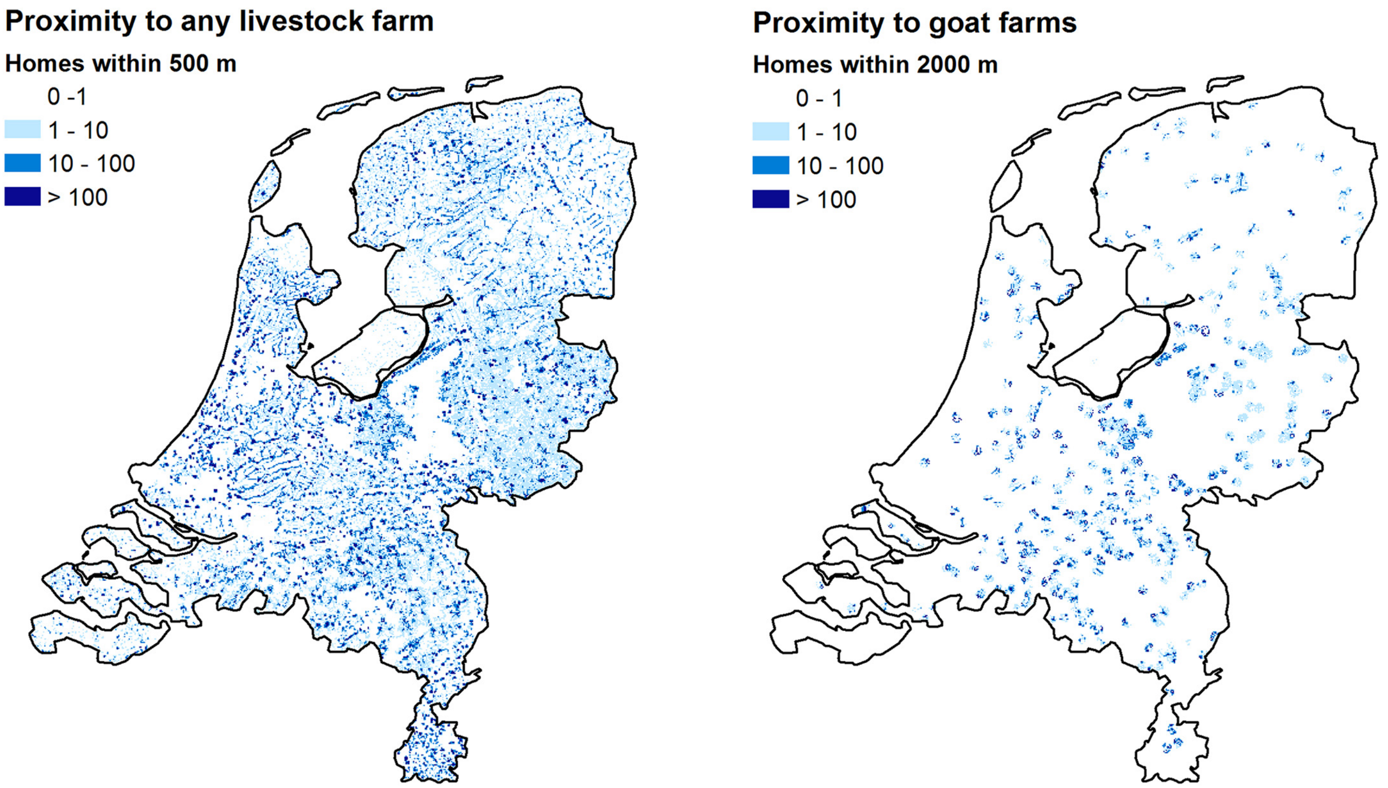

Fig. 1. Proximity to farm-types distinguished in the burden of disease calculation for pneumonia, asthma and COPD, the Netherlands, 2015, for homes within 500 m from any livestock farm and within 2000 m from goat farms.

Lactamase (ESBL) and plasmid-encoded AmpC (pAmpC)-producing *E. coli* in humans can be attributed to non-foodborne transmission from farm animal and environmental reservoirs, most of which can be attributed to poultry and cattle as a whole (Table 3; Mughini-Gras et al., 2019). In contrast, 19% is attributable to food-borne transmission and 67% to person-to-person transmission (Mughini-Gras et al., 2019). For other types of antimicrobial resistance such attribution has not been made but an indication of the link between, for example, Methicillin-resistant *Staphylococcus aureus* (MRSA) and livestock is that 28% surveillance samples in 2015 were of a livestock-associated strain (Veldman et al., 2016). Besides complicating the treatment of human infections, this carriage of resistant microorganisms has additional consequences, such as the requirement of isolation nursing in Dutch hospitals of farmers with a high likelihood of carrying antimicrobial resistant microorganisms (Werkgroep Infectiepreventie, 2012).

Compared to the recent source-attribution effort indicating the State of antimicrobial resistance, the use of various antimicrobials is as Pressure indicator more indirectly related to human health effects, but it does give an indication of a wider spectrum of resistance patterns and it becomes increasingly clear that reducing antimicrobial use leads to a decrease in microbial resistance against antibiotics in animals (Dorado-García et al., 2016; Tang et al., 2017). For example, in the Netherlands between 2009 and 2017, antimicrobial use declined in broilers from 36.8 defined daily dosages per animalyear (DDDA_{NAT}) to 9.4, in pigs from 20.5 to 8.7 DDDA_{NAT}, in veal calves from 33.8 to 20.1 DDDA_{NAT} and from 5.8 to 3.1 DDDA_{NAT}, in dairy cattle (Table 3; Supp6). The reduction between 2009 and 2014 seems to have led to a reduction in antimicrobial resistance in animals ranging from 8% in broilers to 79% in dairy cattle (Dorado-García et al., 2016).

3.2.3. Impact category 7: odor annoyance

In 2016, the percentage of the Dutch population that is severely annoyed by odors from agricultural activities was estimated to be 2.5% (Table 3; Supp7), and is assumed to relate mainly to livestock production processes. This percentage is comparable to annoyance related to sewage systems (2.4%), lower than the percentage of persons severely annoyed by odors from barbeques and recreational open fires (4.4%) or fireplaces (3.9%), but higher than the percentage of persons severely annoyed by odors from industry (1.3%) or restaurants (1.1%) (Poll et al., 2018; Supp7). The percentage reporting severe annoyance related to agricultural activities differed across regions, with the highest percentage (4.8%) in the north and the lowest percentage (1.7%) in the west. In the south, which has several livestock dense areas, the percentage of severe annoyance related to all agricultural activities is about 3.1%, while the odor annoyance specifically related to animal housing in the livestock-dense regions in the south, according to a different survey, is estimated to be about 2%, but in certain municipalities up to 8% (Supp7). Odor annoyance is thought to mainly relate to pig farms and much less to cattle farms (Table 3; Supp7).

3.2.4. Impact category 8: noise

Noise annoyance related to livestock production processes is mainly associated with the transport of animals, feed and manure. Traffic in general is also the main source of noise annoyance in the Netherlands, with about 9.3% of the population reporting severe annoyance with road traffic. Annoyance is lower for main roads (2.5% for a maximum speed of 80 km/h) than for roads with lower speed limits (4.1% for roads with a maximum speed of 30 km/h, 5.6% for a maximum speed of 50 km/h) (Poll et al., 2018; Supp8). No data is available for noise related to traffic specifically due to livestock production processes, nor can differences between animal sectors be inferred, but differences are expected, since between sectors there are large differences in the frequency of animal replacement, milk collection (dairy farms only), deliveries and manure removal.

3.2.5. Impact category 9: incidents manure fermentation systems

Manure fermentation systems, which convert manure to biogas and re-usable digestate, may pose a risk of gas leaks or explosions, potentially affecting the health of persons living near these systems. Two recent local incidents exemplary of the risk were the release of flammable and toxic biogas, in 2014, which could have but did not cause accidents; and the death of three persons performing cleaning in a manure fermentation system in 2013 (Dutch safety board, 2014; Dutch safety board, 2016). For explosion risk the safety target distance between manure fermentation systems and living areas is declared at 30 m by the Association of Netherlands Municipalities (VNG) as the competent authority for manure fermentation systems. In the Netherlands about 100 homes (mainly those of farmers exploiting the manure fermentation systems) are situated within this distance (Supp9). Legally, binding distances to vulnerable objects, such as homes, are only found for very large manure fermentation systems falling under the Seveso III directive (2012/18/EU). Most manure that is processed by manure fermentation systems comes from pigs (55%) and cattle (40%) (Table 3; Supp9).

3.3. National environmental impacts

Estimates of national environmental impact are presented in Table 4. Indicators describing the nutrient-related effects on soil, groundwater, and terrestrial nature indicate that livestock production contributes significantly to the Pressure of nitrogen and phosphorus transfers to the soil, and nitrogen deposition. The maximum acceptable nitrate concentration per L of upper groundwater, furthermore, is exceeded in most regions. Pesticides applied for the purpose of livestock production appear to have a relatively low Impact on the surface water ecosystem but the Impact of livestock-related pesticide application on drinking water quality are comparable to the average Impact on drinking water quality of pesticides use in the Netherlands.

3.3.1. Impact category 10: nutrient-related impacts on soil functioning

Soil functioning is the ability of soils to provide a variety of functions, such as primary production, carbon sequestration, nutrient retention, water retention and natural attenuation. It is affected by several processes related to intensive agriculture, for example by soil compaction through the use of heavy machines, but also by a higher supply of nutrients than can be taken up by plants (Supp 10). The high supply of nutrients can be traced to Dutch livestock production via two overlapping routes. First, Dutch livestock produces manure containing nitrogen and phosphorus (497 million kg of nitrogen (N) and 79 million kg of phosphorus (P) in 2015)(CBS, 2019a), which is mainly applied to arable land and grasslands. Second, for the production of livestock feed, nutrients are applied. A large fraction is applied in the form of livestock manure and a smaller part in the form of artificial fertilizer. All nutrients in animal manure, and the part of other fertilizers that are used for the production of livestock feed, can thus be attributed to livestock production (Supp 10).

The fraction of nutrients not taken up by crops or emitted to air is considered to be transferred to soils, which is used here as a Pressure indicator of soil-functioning but is also a Pressure for run-off and leaching of nutrients into groundwater and surface water (impact categories 11 and 12). Transfers of 225 million kg of N (66% of total) and 7.8 million kg (95% of total) of P to soils may be attributed to livestock production in 2015 (Table 4), although total transfers of N (transfer in 2015 was 68% of transfer in 2000) and P (transfer in 2015 was 17% of transfer in 2000) are declining. For both nutrients, cattle contribute most (Table 4; Supp10). Approximately 56% of the soils to which the nutrients are transferred was found to be phosphate-saturated in 1992–1998, indicating the sensitivity of soils to such transfers (Supp10). Further, about 30% of the land use for feed production in the Netherlands consists of cropland, which is less able to sequester nutrients than grassland (Supp10). This percentage of cropland is higher than the maximum percentage allowed for deviating from the restriction on the amount of nitrogen that may be normally applied under the European Nitrates directive. This restriction is expanded if farmers have a minimum of 80% grassland (maximum 20% cropland) and fulfill several other criteria, such as measuring soil nutrient concentrations and drafting a fertilization plan.

3.3.2. Impact category 11: nitrate pollution of groundwater

In addition to the unwanted impacts upon soil functioning, nitrogen in the soil, which is largely attributable to livestock production (Supp10), leaches to groundwater mainly in the form of nitrate (NO_3^-). In the Netherlands, the nitrate concentration in the upper groundwater varies among areas with different soil types, with on average 55 mg/L in the sandy soil region, 20 mg/L in the clay region, 69 mg/L in the loess-region and 8 mg/L in the peat region (Table 4; Supp11). In 2012–2015 this led to exceedance of the standard (50 mg nitrate/L) in 47% in the sandy soil region, 8% in the clay region, 60% of the farms in the loess region and none of the farms in the peat region (Table 4; Supp11). The exceedance of standards influences drinking water production and surface water quality. The percentage of farms with exceedance of the standard was different specifically on dairy farms (36% in the sandy soil region, 6% in the clay region, and 41% in the loess region). A precise contribution of livestock production to nitrate leaching, including leaching related to animal manure application on cropland and related to artificial fertilizer application for feed production, was not determined.

3.3.3. Impact category 12: surface water eutrophication

Run-off and leaching of nutrients from soils and groundwater can increase nutrient concentrations in surface waters, contributing to eutrophication. Such eutrophication is indicated by the concentrations of nitrogen and phosphorus in agriculture-specific surface waters (N and P input dominated by agricultural sources), as well as by biological indicators in regional surface waters (as opposed to large, nationally governed waters). Nutrient concentrations in agriculture-specific surface water are expected to be largely attributable to livestock production as most of the nutrients applied to agricultural soils are attributable to livestock production (Supp 10). Between 2011 and 2014, nitrogen and phosphorus concentrations in such waters exceeded the nitrogen standard at about 50–65% of the measuring points in the sand region and in about 40–60% in the clay region, and exceeded the phosphorus standard at about 40–55% of the measuring points in the sand and clay regions (van Grinsven et al., 2017; Table 4; Supp12).

In regional surface waters, the concentrations of nutrients only partly originate from current fertilizer application (35% for nitrogen, 10% for phosphorus), with other sources including main water systems, sewage treatment system effluent, postponed runoff from agricultural land (not related to manure application), and runoff from nature areas (Groenendijk et al., 2016; Supp12). The biological water quality of such waterbodies, in terms of the presence of algae, water plants, macro fauna, and fish in comparison to reference water type-specific minimally disturbed conditions, was considered good in only 5% of the waterbodies (van Grinsven et al., 2017; Table 4, Supp12).

3.3.4. Impact category 13: nitrogen deposition in terrestrial nature

The atmospheric deposition of nitrogen compounds can affect terrestrial ecosystems through acidification and eutrophication (Bobbink et al., 1998). Internationally recognized critical nitrogen deposition loads, below which no harmful effects to specific nature target types occur, have been defined (Van Dobben et al., 2012) and form the basis of the indicator we used. We estimate that about 60% of the surface in nature areas is exposed to higher nitrogen deposition than the critical load values for the specific nature target types (Table 4; Supp13). This excess deposition takes place particularly in the eastern and southern parts of the Netherlands (Fig. 2). Livestock production in the Netherlands contributes roughly 40% to the total nitrogen deposition, mainly through the emissions of ammonia. The largest contribution to the ammonia emissions is from cattle with 63%, followed by pigs with 21%, and poultry with 11% (Supp13). Changes in total nitrogen deposition do not proportionally affect changes in critical load exceedance. When zero emissions from animal husbandry are assumed, the exceedance drops from about 60% to about 15% (Supp13; Fig. 2).

3.3.5. Impact category 14: environmental impacts of pesticides application

About 679 × 10^3 kg (7% of total) pesticides are annually applied to land used for livestock feed production (Supp14) in the Netherlands. The ecotoxicological effects of this application are expressed in Environmental Indicator Units (EIUs), which accounts for differences in toxicity of different pesticides and the spatial pattern of application, and expresses the effects relative to legal standards and derived toxicity criteria, which are different for each environmental compartment. In the groundwater compartment, with drinking water criteria as reference, pesticide application on grass and maize accounted for 902 EIUs/ha in 2016 (Verschoor et al., 2019). This value is comparable to the average for all agricultural sectors and considerably higher than 1, indicating that drinking water criteria are likely exceeded in several areas, but not necessarily in each area (Table 4). In the surface water compartment, with standards for the effects on water organisms as a reference, pesticide application accounted for 0.9 EIUs/ha in 2016 which is 95% lower than the agricultural average (Table 4; Verschoor et al., 2019). Note that this latter value is likely an underestimation, because of omitting pesticide application for other feed sources than grass and maize.

3.4. Global environmental impacts

Table 5 shows global Pressures associated with livestock production in the Netherlands. The global land use and GHG emissions are about twice as large as the national land use and GHG emissions, whereas the global blue water use is about three times greater than the national blue water use.

3.4.1. Impact category 15: greenhouse gas emissions

The contribution of livestock production to emission of greenhouse gases (GHG) has been described extensively (de Boer et al., 2011; Gerber et al., 2013; Herrero et al., 2011; Rojas-Downing et al., 2017). Dutch livestock production is responsible for national emissions of 18 × 10^9 kg CO_2-equivalents in 2015 (Supp15b), 9% of total national emissions (Supp15b). GHG emissions attributable to livestock production mainly originate from feed production, enteric fermentation, manure management and fossil energy use (de Boer et al., 2011; Gerber et al., 2013). Due to the imported feed, a large part of these emissions occur outside the Netherlands. The total GHG emissions related to Dutch livestock production, both within and outside the country, were estimated at 42 × 10^9 kg CO_2-equivalents in 2015, more than twice the national livestock-related emissions (Table 5; Supp15a). The majority of the total GHG emissions (62%) can be attributed to the cattle sector (Table 5; Supp15a).

3.4.2. Impact category 16: land use

The feed produced for Dutch livestock mainly consists of grass, maize, cereals and protein-rich crops such as soy bean. While most of the grass and maize are produced in the Netherlands, most of the cereals and protein-rich crops are imported from other countries within and outside Europe, resulting in a total estimated 2015 land use of 14 × 10^3 km^2 within the Netherlands and a global land use of 26 × 10^3 km^2 (Table 5; Supp16). This land use puts a Pressure on habitat loss and on the globally available land for food production. The dairy cattle sector contributes most to the global land use (44%). Most of this land is grassland and maize land in the Netherlands (Supp16). Pigs and poultry production contribute more to land use in countries from which their food (cereals and protein-rich crops) is sourced. In the Netherlands, land used for the production of livestock feed accounts for about 70% of all agricultural land.

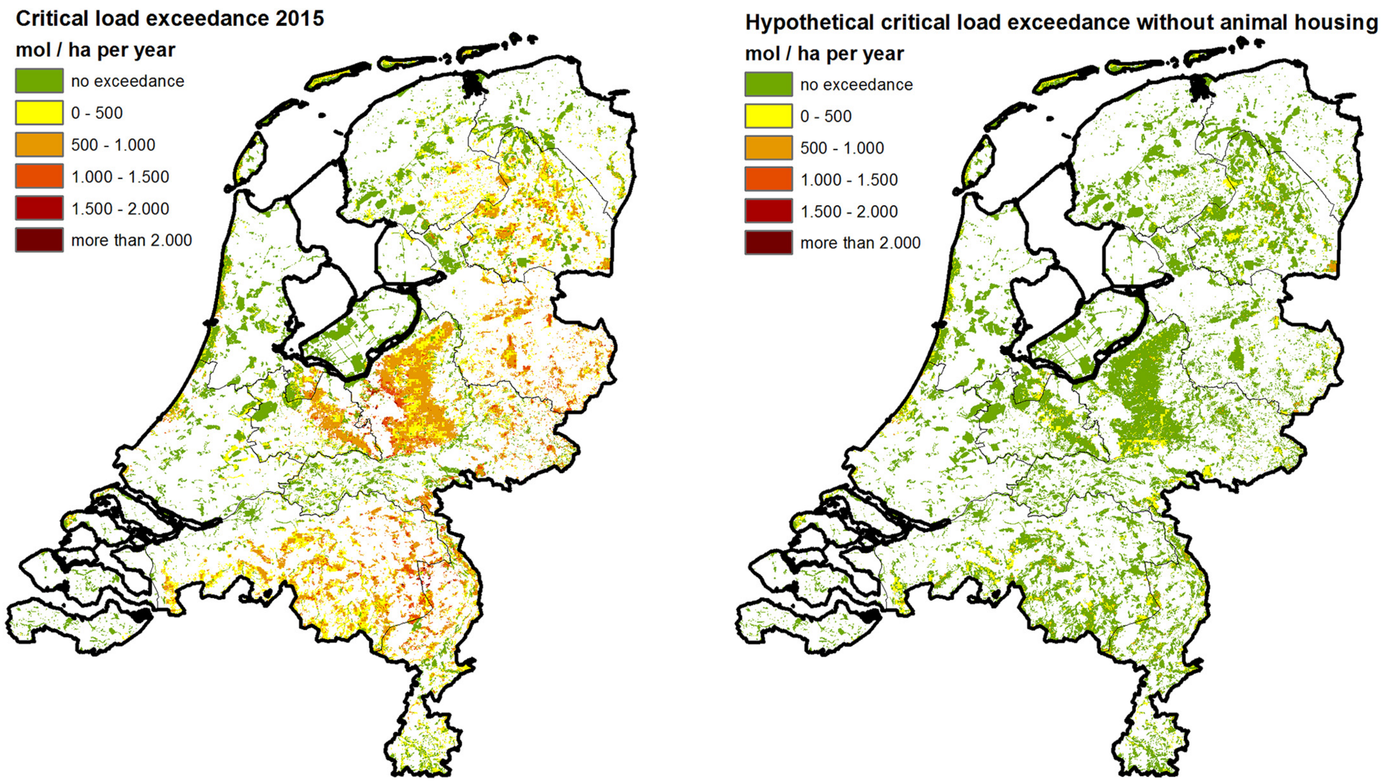

Fig. 2. Critical load exceedance of nitrogen in nature areas in the Netherlands (mol/ha) for 2015 and for a hypothetical situation without animal housing, to illustrate the maximally feasible reduction with respect to livestock production.

3.4.3. Impact category 17: water use

Water for livestock production is mainly required for irrigation of grassland and feed crops, while a smaller share is required for drinking water and cleaning (van der Meer, 2018). Since a large share of the livestock feed is imported, much of this water use takes place outside the Netherlands. In 2015, total water use was an estimated 28×10^7 m^3, which is likely an overestimation because the data for water use per unit of product used are assumed to be overestimated as well (Supp17). About half of this can be attributed to the dairy cattle sector, with pigs and poultry contributing near-equally to the remaining half. Domestically, about 1×10^8 m^3 was used in 2015 for livestock production, or about 2% of total consumption. 31–53 $\times 10^6$ m^3 was used for irrigation and about 50×10^6 m^3 was used for drinking (Supp17; van der Meer, 2018). The tap water use for Dutch livestock production is over 3% of the total tap water use (Supp 17). The national demand for freshwater is currently only occasionally higher than the supply, but such periodical shortages are expected to increase (Ministry of Infrastructure and Environment and Ministry of Economic Affairs, 2015).

4. Discussion

4.1. Human health and environmental impacts

In this study, we provided quantitative estimates of the human health and environmental impacts of the Dutch livestock production system, including feed production and manure management, but excluding slaughtering, retail, and consumption. We collated available information for 17 different impact categories, based on information from a variety of research and policy traditions, and using eight Impact indicators, six State indicators and eight Pressure indicators along the Driver-Pressure-State-Impact chain of the DPSIR framework. For human health impacts, half of the impact categories could be captured in a burden of disease (Bod) measure, i.e. DALYs. These DALYs show that Impacts from livestock-related particulate matter and zoonotic diseases are generally higher than from pneumonia due to proximity to livestock farms and occupational accidents in the livestock sector. A comparatively large beneficial Impact for asthma and COPD may be present due to reduced incidence in the proximity to livestock farms. Estimated contributions ranged from a beneficial effect of 5% of the current BoD for COPD to an adverse effect of about 4% of the BoD for three different health effects: those related to particulate matter, zoonoses, and accidents.

The contribution of livestock production to environmental impacts in the Netherlands ranges from about 2% of the consumptive water use to about 95% of the phosphorus loss. Moreover, the global area of land required for feed production for livestock production in the Netherlands exceeds the area dedicated to all agricultural land use in the Netherlands, necessitating substantial feed imports. Such imports also contribute to global greenhouse gas emissions and water use in a major way.

The national estimates differ across regions and animal sectors. For example up to 8% of residents experience severe odor annoyance in some livestock-dense municipalities, compared with about 2.5% nationally. Different animal sectors had different relative contributions to human health and environmental impacts for most impact categories (Tables 2-5). Cattle contribute most to greenhouse gas emissions, eutrophication, nitrogen deposition, secondary PM_{10}, and land use domestically, whereas pigs and poultry contribute more to land use abroad. Poultry contributes most to the human disease burden related to primary PM_{10} and zoonoses. For some of the other impacts, a quantitative attribution to animal sectors was not obtained, but differences are still expected: for example, in the pressure on the development of antimicrobial resistance due to differences in use of antimicrobials, which is highest in veal calves. In addition to differences across animal sectors, differences within animal sectors may also be considerable due to a variety of adopted farming practices, which were not considered here.

4.2. Strengths and limitations

To our knowledge, this is the first integrated assessment of livestock production effects on human health and the environment at the national level. Such national level assessment adds a novel perspective to previous overviews focussing on farm level or product level, or not quantified at such uniform scale (Aequator Groen en Ruimte et al., 2008; Boone and Dolman, 2010; Bos et al., 2017; Hu et al., 2017). A national level assessment offers insight on the relative contributions of the entire cattle, poultry, and pig sectors rather than just the relative impact of a kg of beef, poultry or pig meat, for example. Such an analysis takes differences in production volume into account. Moreover, a national level assessment allows comparisons with impacts of other economic sectors or the livestock sectors of other countries.

Another distinctive aspect of our approach is the broad and diverse set of 17 impact categories with 22 indicators that were collated. These reflect different classes of risk problems, with differences in probability of occurrence, in extent of damage and in incertitude of the estimates (Klinke and Renn, 2002; Renn, 2006). Such diversity may come at a cost of uniform presentation across impact categories, as illustrated below.

Ideally, all used indicators would express an Impact. However, we only used eight such Impact indicators, among a total of 22, due to limitations in our current knowledge, in availability of data and lack of operational models. These limitations currently preclude operational modelling with integration across the DPSIR causal chain. Thus, while the DPSIR Framework is a very useful conceptual 'Level 2 Relational framework', it cannot act as a ' Level 3 Operational framework' in an integrated assessment (Knol et al., 2010). The difficulty of using Impact indicators can be illustrated for antimicrobial resistance. For this impact category, the presented data on antibiotics use represents a Pressure on antimicrobial resistance in humans and is relevant in existing monitoring programs but currently the relation with resistance cannot be quantified. The additionally presented results from an attribution-study of a specific type of antimicrobial resistance are closer to the Impact, but generalization to other types of antimicrobial resistance is not possible yet, and even that indicator does not indicate the associated disease burden.

Even where Impact indicators were used to express Impact, they were not uniform across impact categories, not even within the same domain. Here we used the DALY metric for four out of the nine human health impact categories, as burden of disease (BoD) measure of human health impact. The DALY is appropriate for health impacts with multiple occurrences per year. Yet, for risk classes characterised by high incertitude in both probability and in impact, e.g. emerging zoonoses, the DALY metric is less appropriate (Klinke and Renn, 2002; Renn, 2006). A BoD measure such as the DALY is also not appropriate to capture odor and noise annoyance which can be considered adverse health effects but do not constitute 'disease' in the medical sense. Forcing such adverse health effects into the DALY metric would devaluate the DALY metric for public health and medical communities. Moreover, in the societal debate and policy arena, prevalence of severe annoyance is the common well-established metric of choice.

Even though a common DALY metric could be assigned to four impact categories, the calculation of DALYs were quite different; some were exposure-driven, while others were disease incidence-driven. For particulate matter, for instance, the estimate is derived from exposure levels, number of people exposed, disease prevalence, and the exposure-response function from the literature. For infectious disease, the estimate is derived from incidence data of the reported diseases, corrected for under-diagnosis and under-reporting, and attributed to specific exposures by expert judgement. Thus, even for this common metric, the nature and size of uncertainties may vary across factors.

Of course our estimates need to be interpreted with some caution and 'ceteris paribus' comparisons may not always be warranted. The different constructs described by the indicators as well as the different research and policy traditions from which the estimates originate affect the location, nature and range of uncertainty (Knol et al., 2009); these vary considerably across indicators. The main sources of uncertainty for each indicator are described in the Supplement. These include uncertainties in model structure, in parameters and in input data of the models. Also, some are epistemic in nature due to incomplete knowledge leading to incertitude, while others are caused by natural (e.g. ecosystem impacts) and societal variability (e.g. demographics affecting disease burden, or annoyance) (Knol et al., 2009). More specifically, for some indicators, uncertainty is related to data availability, as in the case for accidents, for which the only data available included farm employees but not self-employed farmers (Supp4). For the zoonoses indicator, the relative contributions of transmission routes or animals are not precisely known (Supp2). For the particulate matter indicator, little is known about the difference in Impacts of particulate matter from livestock farms compared to other sources, primarily combustion sources of fossil fuels (Supp1). For the asthma, pneumonia and COPD impact category, for which several positive and negative associations with proximity to livestock have been reported, mechanisms are not well understood. This makes it difficult to disentangle the several health effects around livestock farms (including those caused by livestock-related particulate matter). These different knowledge gaps illustrate that the extent to which estimates are backed-up by scientific evidence differs considerably between impact categories. There may also be inherent uncertainty associated with impacts such as with manure fermentation systems wherein the probability of an incident occurring is difficult to estimate (Supp9), or with emerging zoonotic diseases in the future, where the probability, severity, and the specific pathogen that emerges will be inherently uncertain (WHO, 2017a; Supp5). The diversity in location, nature and range of uncertainties preclude uniform consolidation in a uniform index.

Given the diverse nature of effects of livestock production on human health and the environment, further integration across the impact categories is, in our opinion, currently not warranted. Further integration would involve entering multiple normative judgements. For instance about how disease burden compares to biodiversity impacts, or perception issues, or potential climate impacts of greenhouse gas emissions. Or how commonly and frequently occurring impacts compare to rare but potentially high impact events. Integrating disparate indicators is possible, by for example using multi-criteria analysis, but would require subjectively weighing indicators, by users of such analysis. Normative weighing and integration would thus be context dependent and would vary from one situation or country to the next.

Even though including 17 different impact categories, our assessment is not complete and offers an underestimation of the total impact of Dutch livestock production. Some impact categories, such as ecotoxicological effects of heavy metals or non-productive ecosystem services such as the influence of landscape on human well-being, have not been taken into account. Human health impacts and some environmental impacts in other countries, such as those related to ammonia that crosses the Dutch borders, have not been taken into account either. Moreover, other aspects, not related to environment and health impacts, such as the economic viability of the sector (including at the farmer level), agroecosystemic resilience and animal welfare, are relevant in considering policy interventions.

4.3. Implications

Current livestock production with its broad and substantial effects on human health and environment is generally no longer considered sustainable and transition to more sustainable productions systems is a political priority (European Comission, 2018; European Comission, 2019; Ministry of Agriculture, 2018; SER, 2016; United Nations, 2015b). Such transition may be guided by integrated assessments about human health and environmental impacts. Ours shows, to the degree possible, the relative contributions of different animal sectors across different impact categories, and thereby consequences of possible shifts between animal sectors, thus highlighting the possible synergies and trade-offs for alternative policies toward sustainability. It also highlights where more research is needed to reduce major uncertainties that affect decision making.

This assessment took a national perspective, while encompassing transboundary impacts. The national perspective is characterised by high animal density, combined with high human population density, with land use for feed production exceeding the available areal. Similar animal densities, and in some cases also human population densities are also present in regions in Germany (Nordrhein-Westfalen), Belgium (parts of Flanders), France (Brittany), Spain (Catalunia), Italy (Po Valley), the USA and Asia, with hence potentially similar human health impacts. A similarly large import of feed can be found in countries such as Japan (Wang et al., 2018), with related impacts across national or regional borders, as well as a high pressure on the local environment in terms of nutrients. The methodology, impact categories and indicators used in our assessment, as well as methodological lessons-learned are therefore considered useful for broader application elsewhere. Thus, application of similar integrated assessments can be informative at the regional, national and international level elsewhere. For instance, it may help to develop strategic plans regarding new regulations for the European common agricultural policy (European Comission, 2018) or for bringing the European Green Deal into practice (European Comission, 2019).

The differences in impacts across animal sectors that we indicated not only imply that a tailoring of mitigation measures to each sector may help to target specific impacts, but also that other impacts not directly addressed by intervention may suddenly become relevant if shifts in production across sectors occur. In the past, such shifts have occurred following the introduction of European regulations such as the milk quotation system, and large animal disease outbreaks. Such possible shifts illustrate the need of evaluating a wide set of impact categories before introducing large policy programs.

The spatial differentiation of impacts has additional implications. One implication is that municipal, provincial, and national governments are likely to assign different priorities to the impacts distinguished here. Another implication is the relevance of spatial organization of farms in regional planning. Such spatial organization is fundamental for responding to particulate matter-related health impacts, odor annoyance, and nitrogen deposition in terrestrial nature areas, as for example becomes clear from the reduction in external costs that might be obtained by relocating pig production between regions in the European Union (van Grinsven et al., 2018). The distribution of farms in the landscape also affects the spread and emergence of zoonotic diseases and evolution of virulence in pathogens (Boender et al., 2007; Lion and Gandon, 2015; Lion and Gandon, 2016; Messinger and Ostling, 2009).

The difficulty of integrating information from a variety of impact categories illustrates a reality in which impacts may be complex, uncertain or ambiguous and requires alternatives for traditional decision-making, such as scenario construction, precautionary approaches, resilience building and stakeholder involvement (Renn, 2006). To further the quality of integrated assessments toward sustainable livestock production systems, we distil several avenues forward from the lessons-learned from this exercise. One avenue is reducing uncertainties around indicators with potentially substantial impacts, for example regarding mechanisms underlying health effects in the proximity of livestock farms. Another avenue is the development of operational models to better link Pressures, States and Impacts across the causal chain, for example for antimicrobial resistance and ecosystem integrity impacts. In addition, more integrated assessments may benefit from the development and application of approaches to involve stakeholders in assessing specific societal goals or policy-directed questions, and for weighing disparate indicators. These may for example be applied in 'ex ante' evaluations of projected policies toward sustainable livestock production.

5. Conclusions

We were able to describe the effects of livestock production on human health and the environment across 17 impact categories, using eight actual Impact indicators and also approximating Impact with six State and eight Pressure indicators. Livestock production may contribute to up to 4% to the burden of disease related to air pollution, infectious diseases and occupational accidents. Additional types of health effects are annoyance and low-probability, high impact events. Livestock production contributes considerably to many environmental impacts as well, with an estimated contribution of up to 95% for phosphorus transfer to soil, and a considerable contribution of Dutch livestock production to impacts abroad due to imports of feed. Moreover, the impacts of livestock production vary widely across animal sectors. For further guidance of the public debate, additional methods for integration of indicators need to be developed and applied, with stakeholder involvement as a vital part.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acknowledgements

Peter Teunis (Emory University, Atlanta, GA, USA) contributed in an early stage to the quantification of human health impacts. Kitty Maassen, Joke van der Giessen, Titia Kortbeek and Wilfrid van Pelt (National Institute for Public Health and the Environment: RIVM, Bilthoven, The Netherlands) have made valuable contributions to the calculations for the "Zoonoses" indicator. Annemieke van der Wal (RIVM) contributed to the indicators "Nutrient-related impacts on soil functioning" and "Nitrate pollution of groundwater"; Richard van Duijnen (RIVM) provided data for the latter. Dirk-Jan van der Hoek and Arjen van Hinsberg (Netherlands Environmental Assessment Agency, The Hague, The Netherlands) provided the critical load map used to estimate the nitrogen deposition in terrestrial nature indicator. Ton van der Linden, who passed away unexpectedly on January 25th, 2018, contributed to earlier versions of the pesticide application indicator. Pieter Bos, Lars van de Bovenkamp and Theo Viets (Wageningen University and Research, Wageningen, The Netherlands) provided the basis for the calculation of total livestock production estimates, which have been used for the greenhouse gas emissions, land use and water use indicators. Bram Bos (Wageningen Livestock Research, Wageningen, The Netherlands) contributed to discussions in an early stage of the study. Jan Slingenbergh (Food and Agriculture Organization of the United Nations, Rome, Italy) contributed to the design of the study. Linda McPhee (Linda McPhee consulting) checked English language. Finally, we thank two anonymous reviewers for their extensive and constructive feedback on our work.

Funding

This research was carried out in the framework of RIVM Strategic Programme (SPR), in which expertise and innovative projects prepare RIVM to respond to future issues in health and sustainability.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139702.

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