Regional Environmental Change (2018) 18:2403–2415
https://doi.org/10.1007/s10113-018-1335-5

ORIGINAL ARTICLE

Reducing external costs of nitrogen pollution by relocation of pig production between regions in the European Union

Hans J. M. van Grinsven[1] · Jan D. van Dam[1] · Jan Peter Lesschen[2] · Marloes H. G. Timmers[1,2,3] · Gerard L. Velthof[2] · Luis Lassaletta[1,4]

Received: 1 August 2017 / Accepted: 4 April 2018 / Published online: 28 May 2018

Abstract

This paper tests the hypothesis that relocation of pig production within the EU27 can reduce the external costs of nitrogen (N) pollution. The external cost of pollution by ammonia and nitrate from agriculture in the European Union (EU27) in 2008 was estimated at 61–215 billion € (0.5 to 1.8% of the GDP). Per capita it ranged from more than 1000 € in north-west EU27 to 50 € in Romania. The average contribution of pig production was 15%. Using provincial data (224 NUTS2 regions in EU27), the potential reduction of external N cost by relocation of pig production was estimated at 14 billion € (10% of the total). Regions most eligible for decreasing the pig stock were in western Germany, Flemish region, Denmark, the Netherlands and Bretagne, while Romania is most eligible for increasing pig production. Relocating 20 million pigs (13% of the total EU stock) decreased average external costs per capita from 900 to 785 € in the 13 NUTS2 regions where pigs were removed and increased from 69 to 107 € in 11 regions receiving pigs. A second alternative configuration of pig production was targeted at reducing exceedance of critical N deposition and closing regional nutrient cycles. This configuration relocates pigs within Germany and France, for example from Bretagne to Northern France and from Weser-Ems to Oberbayern. However, total external cost increases due to an increase of health impacts, unless when combined with implementation of best N management practices. Relocation of the pig industry in the EU27 will meet many socio-economic barriers and realisation requires new policy incentives.

Keywords Nitrogen · External cost · Spatial optimization · Pig industry · European Union

The original version of this article was revised due to a retrospective Open Access order.

Editor: Kathleen Hermans

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10113-018-1335-5) contains supplementary material, which is available to authorized users.

✉ Hans J. M. van Grinsven
hans.vangrinsven@pbl.nl

Jan D. van Dam
jan.vandam@pbl.nl

Jan Peter Lesschen
janpeter.lesschen@wur.nl

Marloes H. G. Timmers
marloes.timmers@bro.nl

Gerard L. Velthof
gerard.velthof@wur.nl

Luis Lassaletta
Luis.Lassaletta@upm.es

1 PBL Netherlands Environmental Assessment Agency, PO Box 30314, 2500 GH The Hague, The Netherlands

2 Wageningen Environmental Research, Wageningen University and Research, PO Box 47, 6700 AA Wageningen, The Netherlands

3 Wageningen University and intern at PBL, The Hague, The Netherlands

4 Present address: Research Center for the Management of Environmental and Agricultural Risks (CEIGRAM), Universidad Politécnica de Madrid, 28040 Madrid, Spain

Introduction

The average annual consumption of pork products in the European Union (EU27) is about 25 kg per capita, and pig meat is by far the most consumed type of meat (Westhoek et al. 2011). The total EU27 pig stock in 2008 was 155 million, and pig production is often concentrated in regions close to urban consumers to safeguard supply of fresh meat and close to ports to facilitate trade of feed and meat (Roe et al. 2002). Examples of these regions are Bretagne, serving the Paris area (Le Noë et al. 2016), the south of the Netherlands serving the Amsterdam-Rotterdam area and the Ruhr area in Germany, and Cataluña serving the Barcelona area. This causes large regional differences in pig stock and pork self-sufficiency (Fig. 1). The spatial concentration of pig production results in adverse effects on the environment and human health and raises societal disapproval (Abdalla et al. 1995; Wossink and Wefering 2003; Gerber and Menzi 2006; Bonneau and Lebret 2010; Lassaletta et al. 2012; Winkler et al. 2016). Examples of adverse effects are increased atmospheric nitrogen (N) deposition on nature, runoff and leaching of N and phosphorus to groundwater and surface water from storages and application of manures, greenhouse gas emissions (GHG), respiratory diseases due to ammonia aerosols, odour problems, emergence of pathogens that are resistant to antibiotics (MRSA, ESBL) and zoonosis (Rabinowitz and De Conti 2013). Particularly, impacts on terrestrial and aquatic ecosystems are caused by emissions of ammonia and nitrate when these exceed critical loads and levels for protection of these ecosystems. Adverse impacts of pig production are referred to as externalities or external effects of economic activities. They can be viewed as an unintended loss of welfare and therefore a societal cost that hereafter are referred to as external costs. These externalities are partly tackled by farm measures to reduce emissions. Typically, in primary agricultural commodity markets, like the market for meat, prices tend to fall over time (Grilli and Yang 1988) and it is difficult to pass costs of these measures on to the consumer without loss of competitiveness.

Ideally, the optimum level of mitigation of external effects of pig production is determined by comparing the increase of the economic cost of mitigation to the decrease of the external cost. However, expressing external effects in economic (monetary) terms is no standard economic procedure as there is no market for these effects. A proxy for expression of external effects is to quantify ‘willingness to pay’ (WTP) of people to prevent these effects (Tully and Winer 2014). Using various sources of WTP data, Van Grinsven et al. (2013) estimated the total external cost of N pollution from agricultural sources in the EU27 in 2008 at 40–230 billion € per year. The largest part (95%) of these external costs is caused by impacts on human health and ecosystems caused by emission of ammonia (NH_3) from manure production by livestock farming and urea use and by nitrogen leaching and runoff ($N_{L\&R}$), both from the use of manure and synthetic fertiliser.

The current location of pig production sites is a compromise between the lowest production cost (including transport) for the end user (e.g. retail, consumer) and restrictions or advantages imposed by national or regional environmental, spatial and economic policies

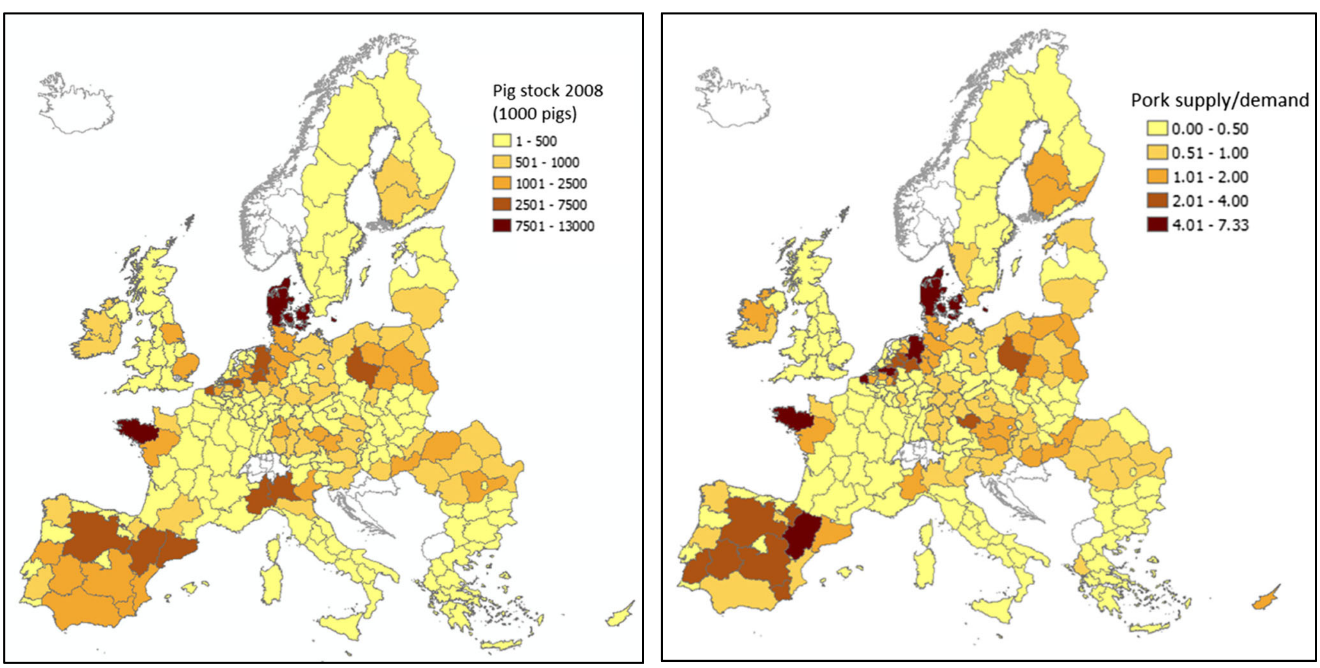


Fig. 1 Pig stock per NUTS2 region in 2008 and degree of self-sufficiency (pork supply/demand) in 2007 (Eurostat)

(Online Resource 1). Aramyan et al. (2011) found major opportunities to reduce economic cost and greenhouse gas emissions when taking the perspective of the European pork sector, including relocation of pork production chain activities to other countries. Relocation of pig production to areas where ecosystems are less sensitive or less N loaded could also reduce external cost of N pollution. Increasing economic efficiency of pork production while decreasing environmental loads should be the preferred outcome of the combined EU policies and investments in agriculture, trade, infrastructure and environment. Since the extension of the EU between 2004 and 2007 with central and eastern European countries with a large potential to increase the productivity and resource efficiency of agriculture, new opportunities have arisen to improve the spatial configuration of feed and livestock production (Van Grinsven et al. 2014). However, relocating pig production will also change transport distances for feed, manure, live pigs and meat products (Willems et al. 2016). This change will create additional direct economic costs and also additional external costs related to emission of nitrogen oxides (NO_x), greenhouse gasses (GHG) and particulate matter (PM) from combustion of fossil fuels. Whether relocation will create a net increase of welfare depends on the balance of changes of internal and external costs of pork production in regions where pig numbers are increased or decreased and costs associated with changed transport of input and output products of pig breeding and fattening. Relocation also offers an opportunity to spatially reconnect crops and livestock systems favouring the improvement of the system nutrient use efficiency due to the regional recirculation of manures (Garnier et al. 2016).

The objective of this study is to explore the potential of spatial relocation of the pig production operations within the EU27 to reduce N emissions and the external costs of N pollution by pig production and to increase N use efficiency (NUE). For this, we quantify N emissions and the external costs of the associated pollution impacts for alternative spatial configurations of pig production at provincial level (NUTS2; Nomenclature of Territorial Units for Statistics in the EU), which are the basic regions for the application of regional policies. We distinguish between current and best management practices to reduce N excretion and N emissions. We also quantify the changes of external costs and direct costs related to changed requirements for transport of input and output products of the pork supply chain. We did not quantify the effects of relocation on the direct economy, as this would require application of a comprehensive economic equilibrium model, which was beyond the scope of our study. In the discussion, we will address barriers, including economic ones, for improving the spatial configuration of EU pig production and governance aspects.

Material and methods

Outline of the model and study design

To assess the external effects of changes of the spatial configuration of pig production, we adapted a conceptual framework for the European pork supply chain in EU27 from Trienekens and Wognum (2009; Fig. 2). We distinguish six different production activities and six transport flows between those activities, which theoretically would lead to 12 sources of emissions of NH_3, $N_{L\&R}$, NO_x, $PM_{2,5}$ (the 2.5-μm fraction of PM) and GHG. However, we can exclude the emissions by the feed and meat processing industry by restricting the analysis to changes of N emissions and external N costs and by fixing total pig production and locations of pork processing in the EU. Feed cultivation and pig production, emissions of NH_3 and $N_{L\&R}$ are the dominant sources of external costs, while emissions of NO_X, $PM_{2,5}$ and GHG are most relevant for external costs caused by transport of materials. Global warming effects by relocation of pig production related to N were not considered; these proved to be nearly climate neutral due to cancelling out of various warming and cooling effects (Butterbach-Bahl et al. 2011). By these assumptions, an assessment of the effect of relocating pig production (grey: NO_x $PM_{2.5}$ and GHG, yellow: NH_3 and blue: $N_{L\&R}$ arrows in Fig. 2) only requires consideration of four emission changes in a NUTS2 region:

1. NH_3 and of $N_{L\&R}$ by change of pig production, which includes breeding, farrowing and finishing (box 4 in Fig. 2),
2. NH_3 and of $N_{L\&R}$ due to the effect of change of regional manure production and the effect of this on the regional use of manure and fertiliser (box 2),
3. NO_x, $PM_{2.5}$ and GHG due to change of distances to transport processed pig feed to sites of pig production (arrow C),
4. NO_X, $PM_{2.5}$ and GHG due to change of distances to transport carcasses and processed meat to consumers (arrow F).

Calculation of N emissions and external costs

The basis of our assessment is emission data for N compounds from agricultural activities and N use in 2008, at a NUTS2 resolution by the model MITERRA-EUROPE (referred to as MITERRA hereafter; Velthof et al. 2009; Lesschen et al. 2011; Online Resource 2). The change of N emissions for alternative spatial configurations of the pig stock is derived from a MITERRA run where the pig stock in every NUTS2 region in 2008 is increased by 1000 pigs assuming current practices to reduce N emissions or best practices (Fig. 3, Online Resource 3 and 4).

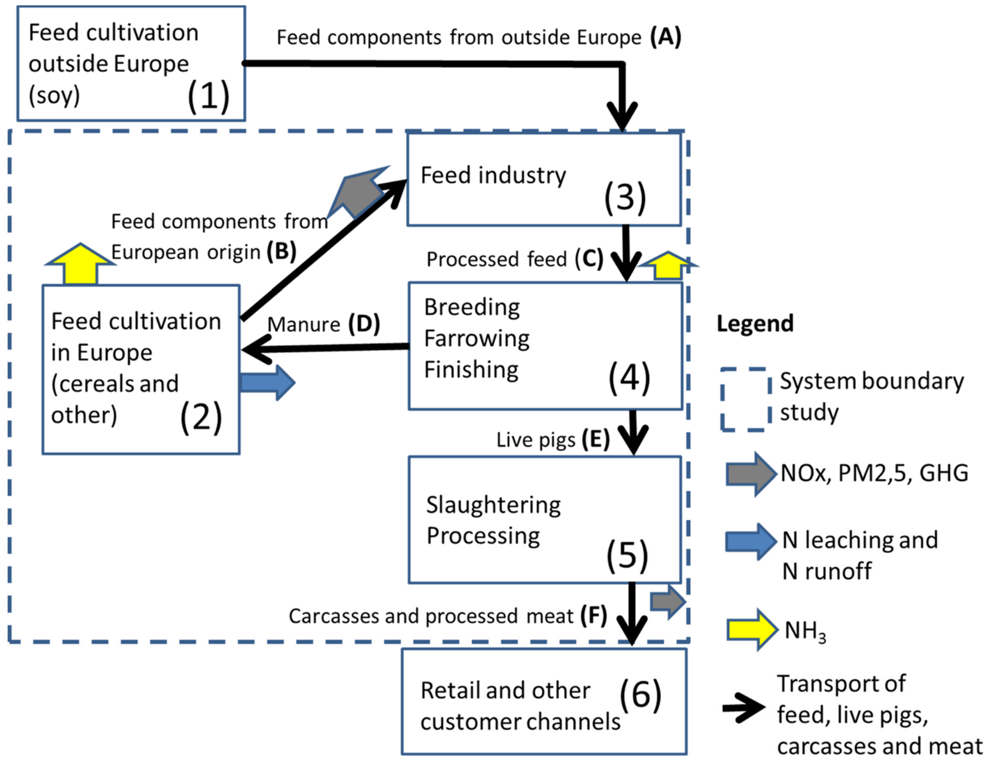


Fig. 2 Conceptual framework for analysis of reduction of external costs of pig production by relocation. Boxes indicate the six different production activities and arrows the six transport flows of the pork supply chain in EU27

The change of external N costs is calculated using the unit N cost method which is based on the willingness to pay to prevent the associated impacts (Van Grinsven et al. 2013). The economic concept of 'stated preferences' (also known as the 'Willingness to pay' (WTP) method (Pearce and Turner 1990)) is used to value damage to ecosystems and human health. Stated WTP tends to increase with income (Bateman et al. 2002) and can be substantially higher than revealed WTP or ability to pay (Van Grinsven 2016), but also can be lower than revealed regulatory public spending (Holland et al. 2015). The

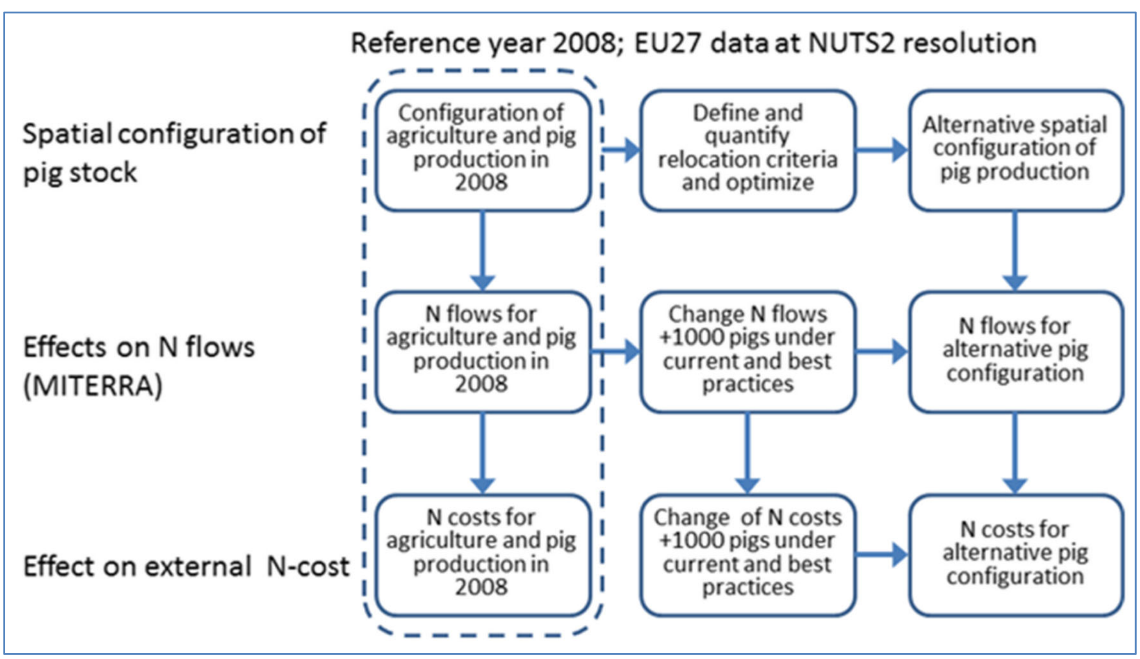


Fig. 3 Schematic overview of calculation of changes of N flows and external N costs for alternative spatial configurations of pig production

external cost of pollution (emissions to air and water) was calculated as

$$\text{Pollution cost} = \text{sum}\,(\text{pollution flux} \times \text{unit pollution cost})$$

Results for increase of external cost per unit of pig production are in Online Resource 5.

External costs of feed cultivation and pig production

Pig production causes a range of negative impacts and risks for the environment and human health. Here, we only consider external costs of damage caused by emissions of NH_3 and $N_{L\&R}$ because these are the dominant sources of external cost (van Grinsven et al. 2013). To estimate the external costs associated with a change of N pollution due to a change of pig population in a NUTS2 region, we multiply the change of N emissions (kg) by the unit N cost (€/kg). Cost per unit of N pollution (Unit N cost) strongly varies between impacts and countries (Table 1 and Online Resource 2). Differences between countries are caused by different relationships between emission, exposure and impact (Brink et al. 2011) and by geographic variation of WTP to prevent the impacts (Sutton et al. 2013). Health and ecosystem impacts of air pollution depend on the spatial configuration of emission sources and exposed population or nature areas and the predominant wind direction. Geographic variation of unit N costs therefore also reflects different population densities and land use for forest and nature. By using the national average unit costs at the NUTS2 level, we ignore variation of the dose response relation between emission and health impacts within a country. Geographic variation of WTP expresses variation of concerns for environmental issues (European Commission 2014a), which correlates to GDP, particularly for the WTP data we used for aquatic ecosystem impacts (Gren 2008). For assessments of external costs of impacts of N pollution on human health, there is no GDP effect because we used a fixed value of a life year throughout the EU27 (VOLY of 40,000 euro; Desaigues et al. 2011). We considered a fixed value the only ethically defensible option, as country-specific values would imply that a human life in EU countries with low GDP is worth less than in countries with high GDP.

External and internal costs of transport

We assumed uniform external and internal costs of transport of feed and pork in the EU. Resulting total external cost of transport in the EU is only 2% of the external cost of pig production, and therefore, an increase of external costs of transport when relocating pig production can be neglected in accordance with findings by Winkler et al. (2016). Also, the 'internal' cost of transport of meat is relatively small with 0.013 €/kg pork /100 km, which is about 1% of the total cost of production. So, the relocation of pig production over distances of several hundred kilometres not necessarily affects competitiveness of regional pig supply chains. These results support our hypothesis that relocation of pig production without increase of external and internal transport costs is feasible (Online Resource 6).

Construction of alternative spatial configurations of pig production under current and improved N management practices

We constructed two alternative spatial configurations (at the NUTS2 resolution) of the pig population in the EU while imposing several general restrictions. To maintain supply of pork at EU27 scale at current pork consumption levels, the total pig production in the EU27 was maintained at the level in

Table 1 Marginal external cost of different N threats in EU27 based on willingness to pay between 1995 and 2005 (for background information, see Van Grinsven et al. (2013))

Impact	N compound and flow	Range of mean national unit cost in EU27 (€/kg N)	Countries with low unit costs (€/kg N)	Countries with high unit costs (€/kg N)
Degradation of aquatic ecosystems (fresh and marine)	N runoff, N leaching, N deposition due to emission of NH_3	2–80	< 5 e.g. Baltic states, Bulgaria, Romania	> 40 e.g. Denmark, Sweden
Degradation of terrestrial ecosystems	N deposition due to emission of NH_3	0.1–4.9	< 0.5 e.g. Greece, UK, Spain, Ireland	3–5 e.g. Austria, Germany, Netherlands
Human health impacts due to secondary particulate matter	Emission of NH_3	3–46	< 5 e.g. Lithuania, Finland, Ireland, Estonia	> 30 e.g. Belgium, Netherlands, Czech Republic, Germany, UK
Human health impacts due to nitrate in drinking water	Leaching of NO_3^-	0.1–2.4	0.2 e.g. Ireland, Netherlands, UK, Spain	> 1 e.g. Austria, Belgium, Germany, Italy

2008. We did not consider interaction with other livestock types and kept population of other livestock categories equal to 2008 values. We set the maximum change of the pig stock in a NUTS2 region to two million head. A maximum decrease of the pig stock by two million pigs recognises the contribution of regional pig sector to current economy and employment and the generally slow change of size and structure of the agricultural sector. A pig stock of two million head is assumed to be an adequate amount to develop an economic vital pig supply chain in a region starting a pig sector (personal communication K. Poppe and W. Baltussen 2014). When such a supply chain and the associated transport, knowledge and financing infrastructure are not yet present, this will be a barrier for relocation. We also did not allow the total manure N production by livestock in housing to exceed the application limit of 170 kg/ha N for arable land, as set by the Nitrates Directive for regions in the EU vulnerable to nitrate leaching (NVZs; Online Resource 7).

Construction of the first configuration (Config-1) was targeted at minimising the external N cost per capita. For Config-1, the pig stock in a NUTS2 region in 2008 was multiplied by a NUTS2-specific redistribution factor, F1. F1 is the ratio of the sum of mean EU values of (A) external N cost per capita region and (B) the increase of the external N cost per pig over the sum of both costs (C, D) for a NUTS2 region (Online Resource 7). F1 ranges between 0.2 and 9.4. In Config-1, nearly 50 million pigs are relocated, corresponding to one third of the total pig stock in the EU. For example for the NUTS2 region Münster in Germany with a pig stock of 3.77 million head in 2008, F1 was 0.85 (= (A + B)/(C + D) = (330 + 110)/(379 + 141)), giving a first optimal pig stock of 2.36 million head. The final stock was 2.57 million head after accounting for the general restrictions described previously.

The N emissions associated with pig production and use of pig manure in the EU27 are expected to change considerably in the coming decades due to knowledge transfer and convergence of practices. The effect of changing the spatial configuration of pig production on the N flows was therefore analysed for current practices for feed conversion and emission control in the EU (CP) and also assuming best available technology and practices (BP). As currently N excretion rates of pigs and emission factors for NH_3 from housing and storage and at manure application are the lowest in the Netherlands, the Dutch practice as parameterized in MITERRA was used as BP. BP could represent a hypothetical situation in the twenty-first century when all EU countries have adopted Dutch practices for pig feed conversion efficiency and NH_3 emission reduction techniques for pig housing, manure storage and manure application. One variant of Config-1 was evaluated where BP was applied uniformly and another where BP was restricted to new pig production in regions receiving pigs. Convergence of costs per unit of labour, capital and energy was not considered.

The second configuration (Config-2) integrated two targets for relocation. The first target was reduction of exceedance of critical loads for atmospheric N deposition on terrestrial ecosystems, to improve compliance with the goal of the EU National Emission Ceilings directive (EC 2001). EU air pollution policies to protect terrestrial ecosystems are one of the oldest N policies and, different from health and aquatic problems, have regionally differentiated CLNs, making relocation of N emission sources a sensible solution. The required decrease or allowable increase of the pig stock in a NUTS2 region to meet the critical deposition load that protects 90% of the ecosystems (hereafter referred to as CLN) was calculated as the ratio of the exceedance (or undershoot) of the CLN (kgN) and the ammonia emission per pig (kgN). For the CLN data, we used $0.50^0 \times 0.25^0$ grid data provided by Posch et al. (2011) (Online Resource 8). The second target was that feed cereals for pig production in a NUTS2 region are cultivated in the same NUTS2 region. For this, the required change of the pig stock in the NUTS2 was the increase or decrease of the pig stock inferred from the cereal surplus or deficit. This surplus or deficit was equal to the cereal production in the NUTS2 region after subtracting demands for food, feed for other livestock types and industry (Online Resource 8). Both targets were combined by iteration, taking into account the general restrictions as used for Config-1.

Satisfying this second target will increase closure of regional nutrient cycles and may stimulate the local application of N in pig manure, and by that, increase the nitrogen use efficiency (defined as the ratio of N removal by crops over total N input to the soil). By this, it addresses the goal of the recent communication of the European Commission (2014b) on 'Towards a circular economy'. A closure of regional feed-manure cycles will also reduce the transport distance and costs for feed cereals and manure (Fig. 2). Config-2 relocates 55 million pigs.

Results

External cost of N pollution from agriculture and pig production in 2008

The total external cost due to emission of NH_3 and $N_{L\&R}$ from agricultural sources in 2008 under current N practices (CP 2008) was 138 billion €, with an uncertainty range of 61–215 billion € due to uncertainties in unit costs. External costs were higher than estimated in Van Grinsven et al. (2013), because we increased the unit cost for health impacts of ammonia in view of improved evidence of effects of ammonia aerosols (Online Resource 2). Current external cost range represents 0.5 to 1.8% of the GDP of the EU (in purchasing power parity) and reflects the associated loss of welfare (Van Grinsven et al. 2013). The shares of individual impacts in the total external N costs were 26–36% for impacts of NH_3 emission on human health, 0–1.3% for nitrate leaching on human health, 3–4% for impacts of NH_3 deposition on terrestrial ecosystems, 22–26% for NH_3 deposition on aquatic ecosystems and 38–43% for impacts of N leaching and runoff on aquatic ecosystems. The large difference between the external cost for impacts on terrestrial and aquatic ecosystems is caused by the differences in unit costs (Table 1) and in part are an artefact of differences in underlying surveys into WTP (Brink et al. 2011).

Total external N costs per hectare could be viewed as an impact weighted sum of emissions of individual N compounds, where each combination of N emission and impact is weighted according to the WTP to prevent the associated impact. Regions with high external N costs and a large share in external N costs by pig production are particularly eligible for reducing the pig population. These regions are Bretagne, Denmark, the southeast of the Netherlands and parts of Belgium, Northwest Germany, western Spain and northern Italy (Fig. 4).

The mean external N cost per capita for the NUTS2 regions was 354 € with a range between 6 and 1786 € (Fig. 4). Cost per capita is the highest in regions with a, relatively, intensive agriculture, high livestock density and low population density, like Ireland, Denmark, Bretagne and Northwest Germany. The N pollution costs for the island of Ireland and the peninsula and islands of Denmark are also high, because of impacts on the large area of marine ecosystems in the national territory. The average contribution of pig production to external cost was 15%.

Presented results for effects of relocation on emissions and external costs in both configurations focus on the regions with the biggest change in pig stock adding up to total relocation of about 20 million pigs.

Alternative spatial configurations of pig production

To achieve a net reduction of external N cost per capita at current practices (Config-1), the redistribution procedure in general relocates pig production from concentration areas in western Europe to central and eastern Europe (Fig. 5; Online Resource 7). However, pigs are also relocated from central Spain to the east coast of Spain, which includes the pig intensive Cataluña region. The total pig stock in the four pig delivering NUTS2 regions in central Spain (Aragon, Castilla y León, Castilla-la Mancha and Extremadura) is 14.3 million on a human population of 6.9 million, as compared to 7.5 million pigs on a human population of 12.1 million in the two pig receiving regions Cataluña and Comunidad Valenciana (Online Resource 10, Table SM15). It is the combination of relatively high ammonia emissions from the large pig stock and a relatively small human population that causes N cost per capita to be higher in the source regions and which drives relocation.

If we consider for Config-2 the criterion of exceedance of critical deposition loads, the required reduction of the NH_3 emission from agriculture to end exceedance is equivalent to the emission from over 800 million pigs, which is six times the current pig stock. This shows that ending exceedance requires reduction of other deposition sources than ammonia emission from pig production. There are only 26 out of 224 NUTS2 regions where the pig stock could be increased without exceeding the CLN. These regions would provide room for a relocation of only 34 million pigs. Some of these potentially suitable NUTS2 regions are in Scotland, Sweden and Finland, which countries have large areas of (semi-) natural land and extensive agriculture. A barrier to increase pig production in these regions could be the wish to keep these currently relatively 'clean' regions clean in the future. Config-2 also yields NUTS2 regions suitable for expanding the pig sector in Bulgaria, Germany, France, Poland and England (Fig. 5). There is even some room for expansion in the already livestock intensive NUTS2 regions in the Flemish region, because terrestrial ecosystems in these regions are less sensitive to impacts of N deposition as expressed by relatively high CLN values. Values of CLN for Romania and most NUTS2 regions in Bulgaria, Slovakia, Slovenia, as well as in Spain, Portugal

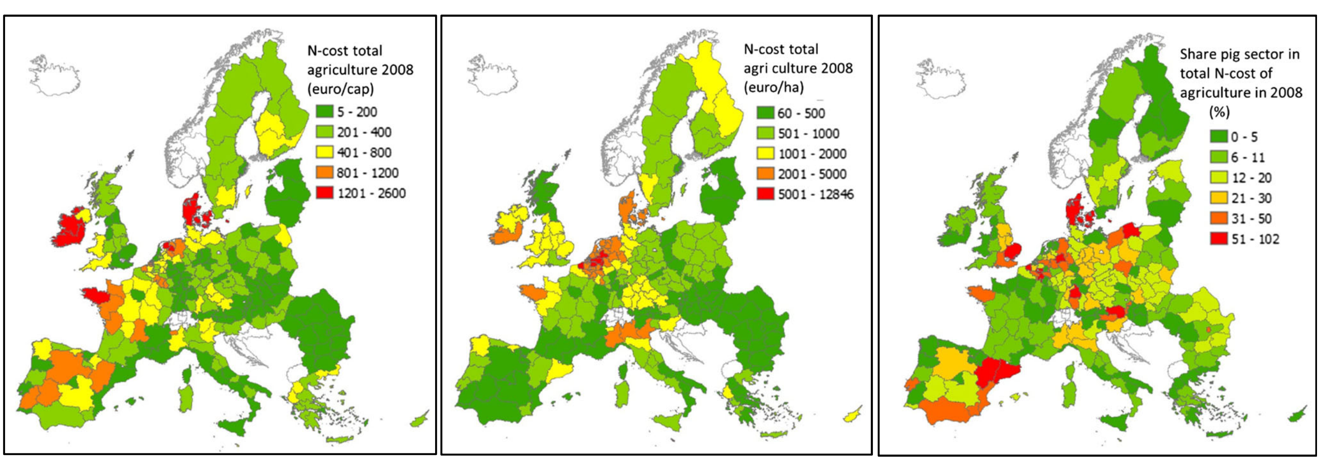
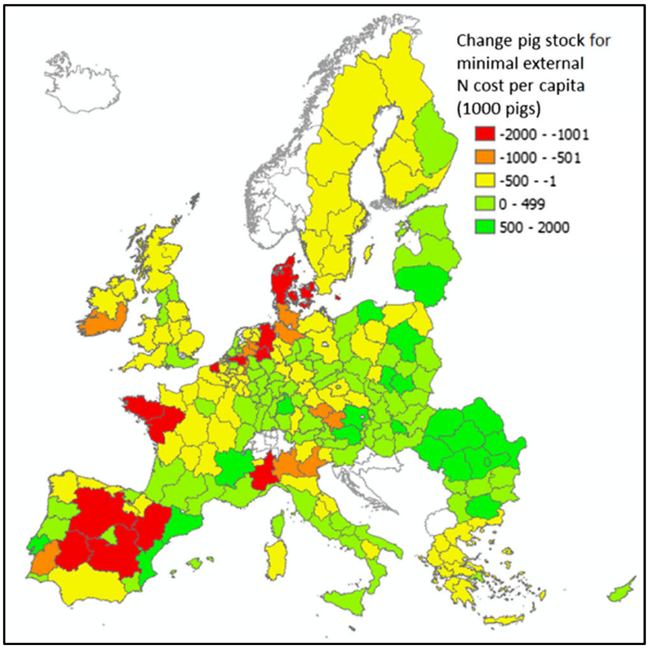


Fig. 4 Total external N cost of agriculture in EU27 in 2008 due to NH_3 emission and $N_{L\&R}$ (N leaching and runoff) for current practices, expressed per capita (left) and per hectare (middle) and the share of these costs by pig production (right; notice that the scale is different for the three figures)



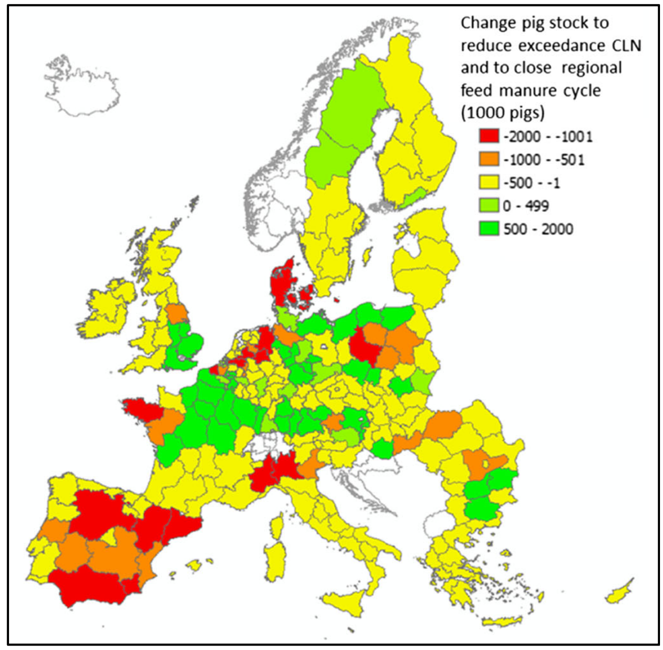


Fig. 5 Change of the pig population in NUTS2 regions for two improved configurations. Left Config-1 to minimise external N cost per capita in EU. Right Config-2 to simultaneously reduce exceedance of critical deposition loads on terrestrial ecosystems and to improve closure of regional feed-manure cycles. The maximum change of the pig population in a NUTS 2 region is set at two million heads

and Greece, are relatively low compared to those in NUTS2 regions in western Europe. These low values can be related to absence of submission of national CLN data. In this case CLN is derived by the UNECE Coordination Centre for Effects (CCE) generally using the chemical criterion, which gives low CLN for low precipitation surpluses in southern and eastern EU (Posch et al. 2011). The mean CLN values for the NUTS2 regions in the east of the EU is 5.0 kg N/ha ($n = 31$) and in central EU 4.4 kg N/ha ($n = 30$) as compared to 9.3 kg N/ha ($n = 84$) in the west, 3.6 kg N/ha ($n = 65$) in the south and 3.0 kg N/ha ($n = 18$) in the north (Online Resource 2).

Evaluation of the suitability of NUTS2 regions in Config-2 to increase the pig production based on the criterion of feed cereal supply yields much more potential for relocation of the pig production. If we combine both criteria for Config-2, the NUTS2 regions eligible for reduction of the pig stock are similar to Config-1 but now also include Cataluña, central Poland and some NUTS2 regions in Romania and Hungary (Fig. 5). Denmark has an intermediate position with, on the one hand, its large cereal surpluses and, on the other hand, high levels of exceedance of CLN. Eligible regions for expansion of pig production are quite different from Config-1, now including all NUTS2 regions in central and Northern France (except Bretagne), southern and eastern Germany, the Baltic states and large parts of Poland. In Config-2, these regions could accommodate an increase of the pig population by several million head. In contrast to Config-1, Config-2 does not yield potential to expand pig production in the new central and eastern EU member states, except in a few NUTS2 regions in Hungary and Bulgaria.

Effects of relocation on emissions and external cost

EU27 level

Config-1 reduced external cost by almost 14 billion € relative to the reference situation in 2008 under current practices (CP). An EU-wide implementation of best N management practices reduces the external cost of N pollution also by nearly 14 billion € (Table 2). The combination of BP and Config-1 does hardly reduce total external cost below 14 billion €, because the additional decrease of external cost by BP in regions where the pig stock is increased is cancelled out by a lower decrease of external cost in regions where pig stock is decreased and also BP is applied.

If BP is only applied to relocated pig production in NUTS2 regions receiving the pigs (Config-1A), the total external cost further decreased by just over 1 billion €. In Config-1, part of pig production is moved to east European countries where the external cost of one unit increase of N emission is relatively small in view of still low GDP (Table 1).

Relocation of pigs in Config-2, aimed at reducing exceedance of CLN on terrestrial ecosystems, increases the total external cost of N pollution by more than 4 billion € (Table 2). This indicates that the increase of external cost due to impacts of NH_3 on human health and aquatic ecosystems and of $N_{L\&R}$ on ecosystems overwhelms the decrease of external cost by impacts of NH_3 deposition on terrestrial ecosystems. When Config-2 is combined with BP, it yields a modest decrease of external N cost by 2 billion €. When BP is only applied to NUTS2 regions where the pig stock is increased (Config-

Table 2 Total external cost due to emission of NH_3 and $N_{L\&R}$ from agricultural sources in EU27 in 2008 under current practice (CP 2008) and cost change due to relocation and introduction of best N management practices (BP)

		NH_3 emission (health)	NH_3 deposition (terrestrial ecosystems)	N leaching (health)	N leaching (aquatic ecosystems)	NH_3 deposition (aquatic ecosystems)	Total
Billion €							
CP	2008	38	5	1	58	35	138
Change relative to CP 2008							
BP	2008	− 3.5	− 0.5	− 0.1	− 7.5	− 1.9	− 13.6
CP	Config-1	− 2.8	− 0.4	− 0.1	− 6.2	− 4.2	− 13.7
BP	Config-1	− 3.1	− 0.3	− 0.1	− 6.1	− 3.8	− 13.4
BP	Config-1A*	− 3.7	− 0.4	− 0.2	− 6.2	− 4.4	− 14.9
CP	Config-2	1.9	0.3	0.0	2.1	0.0	4.2
BP	Config-2	− 0.1	0.0	− 0.1	− 0.5	− 1.2	− 1.8
BP	Config-2A*	− 1.2	− 0.1	− 0.1	− 0.6	− 2.0	− 4.0

*BP is only applied to NUTS2 regions where the pig stock is increased

2A), external N cost decreases by 4 billion €. The cost decrease when applying BP for Config-2 is larger than for Config-1, because in Config-2, pigs are predominantly relocated within the national borders of countries in north-western Europe, with comparably high GDP and unit N costs.

In the next section, we present the results for a selection of individual NUTS2 regions where the configuration resulted in the largest change of the pig stock. The presented selections of NUTS2 regions still represent a policy option for relocation for the EU without a net change of pig production.

NUTS 2 level: alternative spatial configuration of pig stock to reduce external costs per capita (Config-1)

Relocation of 20 million pigs in Config-1 reduces the pig stock in the source regions by 35% and more than doubles it in the regions receiving pigs. Pigs are relocated from

> Denmark, the Netherlands (Noord-Brabant, Overijssel), the Flemish region (West-Vlaanderen), Germany (Weser-Ems, Münster), France (Bretagne, Pays de Loire), Spain (Aragón, Castilla y León, Extremadura, Castilla-la Mancha) and Italy (Piemonte, the Po valley) to:
> Nearly all NUTS2 regions in Romania (Centru, Vest, Nord-Vest, Sud, Sud-Vest, Sud-Est, Nord-Est, Bucuresti), Spain (Cataluña, Comunidad Valenciana) and Austria (Steiermark)

Relocation transfers about 70 Gg N as ammonia emission and 60 Gg N as leaching and runoff, reducing both emissions by about 10% in the source regions and increasing ammonia emission in the receiving regions by more than 40% and N leaching and runoff by 20% (Online Resource 9 and 10). Combination with introduction of best practices in the pig receiving regions halves the increase of ammonia emission. Leaching and runoff are only marginally reduced, because the effects of reduced N excretion per pig are counteracted by the increase of the N content in applied manure, which is due to measures to reduce N losses as ammonia from housing, manure storage and at manure application. The adoption of best practices is a condition to achieve a net reduction of N emissions when relocating pig production. Under CP the decrease of the external cost of N pollution per capita in the source regions is 116 € (19%) and much larger than the increase by 38 € (10%) in pig receiving regions. Under BP, the decrease of external cost is 93 €/cap and the increase 24 €/cap, respectively (detailed results in Online Resource 9 and 10).

NUTS 2 level: alternative spatial configuration of pig stock to reduce exceedance of critical N loads and close feed-manure cycles (Config-2)

For Config-2, about 25 million pigs are relocated from 15 source NUTS2-regions to 13 receiving regions. Source regions have the highest exceedance of CLN and/or insufficient regional supply of feed cereals. In contrast to Config-1, pig production is relocated mostly within western EU. Pigs are relocated from

> Denmark, the Netherlands (Noord-Brabant, Gelderland), the Flemish region (West-Vlaanderen), Germany (Weser-Ems, Münster), Poland (Wielkopolskie), France (Bretagne), Spain (Andalucia, Aragón, Castilla y León, Cataluña, Región de Murcia) and Italy (Piemonte, Lombardia) to:
> Bulgaria (Severoiztochen), Germany (Oberbayern, Mecklenburg-Vorpommern, Braunschweig, Thüringen), France (Centre, Poitou-Charentes, Picardie, Haute-Normandie, Champagne-Ardenne, Nord—Pas-de-Calais, Poland (Dolnoslaskie), United Kingdom (Eastern)

While the source regions are almost identical to those for Config-1, 10 out of 13 NUTS2 regions in Config-2 receiving pigs are located in Germany and France. This indicates that the relocation of pig production within the national borders of France and Germany is an option to reduce exceedance of critical N loads and close nutrient cycles. The total pig population in the receiving regions increases by a factor of five, while it decreases by 35% in the source regions. Combined with introduction of BP in NUTS2-regions receiving pigs, relocation reduces ammonia emission by 33 Gg N but there remains a net increase of N leaching and runoff by 15 Gg. BP reduces leaching and runoff from 4.4 to 3.5 kg N/pig, but this is not enough to compensate the effect of the increase of the pig stock.

Config-2 does not reduce the total external N cost of the pig sector for the selection of regions. The external cost in the 15 source regions decreases by 2.9 billion € per year (under CP), while it increases by 3.1 billion € in the receiving regions (under BP). Config-2 under CP reduces the external N cost in the source regions from 672 €/cap to 574 €/cap and increases the external cost in the receiving regions from 401 to 682 €/cap under CP and to 514 €/cap under BP. So after relocation mean, external cost per capita in the pig source and receiving regions would become similar. For details, see Online Resource 9 and 10.

Relative to 2008 (and under CP), the average N deposition in the source regions decreased by 4 kgN/ha (25%) and cumulative exceedance of CLN in natural and semi-natural land by 2.5 Gg N (17%) (Online Resource 10). In the receiving regions and under BP, the average N deposition increased by 2.3 kgN/ha (19%) and cumulative exceedance increased by 1.5 Gg N (70%). But in both scenarios, the net cumulative exceedance for the total selection of 28 NUTS2 regions hardly changed. Yet, Config-2 reduced the external N costs due to impacts of N deposition on terrestrial ecosystems by almost 70 million €/year (15%) because exceedance was relocated to regions with lower WTP to prevent impacts of N deposition (lower unit N costs). While (under BP) there is a net increase by almost 100 million € (more than a doubling relative to costs in 2008) in the regions receiving pigs, there is a net decrease of external costs by more than 160 million € (40% of the cost in 2008) in the source regions. After relocation, the CLN remained to be exceeded in all selected 28 NUTS2 regions, except for Oberbayern in Germany. Relocation decreases N soil surpluses in the source regions and increases N soil surpluses in the receiving regions, but hardly affects soil N use efficiencies (Online Resource 9).

Discussion and conclusion

Potential of relocation from an EU perspective

Although our calculation procedure introduces inaccuracies in results at NUTS2 level by using national excretion and emission factors to calculate N excretion and losses of NH_3, NO_X and NO_3 and national unit costs, while using NUTS2 specific data for, e.g. land use, livestock numbers and fertiliser use, we can make some robust observations and conclusions. The presented alternative spatial configurations are meant to be explorative rather than prescriptive. A first observation is that the current exceedance of critical N levels and N loads in water and air for ecosystems and human health does not provide much room to increase pig production, or in fact any N emitting activity, anywhere in the EU, when this increase is accompanied by additional N emissions. A second observation is that the mean external cost per fattening pig in the EU of 142 € is similar to a production cost of 181 € and to current market prices around 170 € (European Commission 2015). This suggests that an average pig farmer loses money when accounting for farm labour. Both observations question whether the current volume and practices of pig production create welfare in the EU. A first conclusion is that relocation of pigs within the EU can reduce N emissions and associated external costs up to about 10%. The reduction of the associated external N cost of N pollution is primarily caused by relocating pigs to regions with lower income and WTP to prevent these impacts. A second conclusion is that expansion of the pig sector in a region should be accompanied by introduction of best N management practices. This secures a net reduction of emissions and external costs of N pollution in the EU as a whole and prevents an increase of N pollution and external costs in regions where the pig stock is expanded. The important question is if the decrease of N emissions in western EU is justified given the increase of emissions in central and eastern EU. An important condition for pig relocation to reduce external N cost is that N emissions are moved to regions where they either cause less impacts or where WTP to prevent these impacts is lower. The latter condition raises an ethical issue, as GDP and WTP may increase in the future, particularly when relocation is not combined with introduction of best practices. Relocation is attractive, when there is a net decrease of external cost at EU level, the resulting external cost per capita in the pig receiving regions is not exceeding that cost in the source region and the receiving region benefits economically from expansion of the pig industry. It is important that these costs and benefits are communicated to the general public before relocation is considered. This will both modify attitudes (and WTP) of people and can support regional policy decisions on relocation. Preferably, other environmental issues should then also be addressed like, phosphorus, odour, resource efficiency, noise, increased traffic, risks of zoonosis and impacts of other livestock sectors.

Potential of relocation from a regional and national perspective

External N costs of N deposition on terrestrial ecosystem at national level can be reduced by relocation of pig production within a country. Relocating NH_3 emissions to less polluted areas within a country, however, will hardly reduce external costs. The reason is that total external N costs are dominated by health impacts of ammonia containing aerosols and impacts of N inputs to aquatic ecosystems and that we use uniform dose response relationships for health impacts of NH_3 and unit N costs within a country. Perhaps the best example for relocation within a country is to move part of the production in Bretagne in France to regions in the north and center of France. In these regions, there is ample supply of feed cereals and they are closer to consumers in the Paris regions, as Le Noë et al. (2016) and Garnier et al. (2016) also recently concluded. Other examples are in Germany and Poland. In view of the alarming increase of imports of feed and agricultural surpluses of reactive N (Lassaletta et al. 2014), there is also an eminent need to reconfigure pig production within Spain, but there seem to be few options to relocate in Spain itself. Our optimization algorithm sometimes increases the pig stock in regions where pig production already is concentrated like, e.g. Cataluña, which may seem counterintuitive. However in the case of Spain, moving four million pigs in Config-1 from the two NUTS2 regions Aragón and Castilla y León to the two regions Comunidad Valenciana and Cataluña reduces total N cost in the first two regions by 0.63 billion €, while increasing the total N cost in the two pig receiving region by 0.35 billion € (Online Resource 10, Table SM15). So relocation gives a net benefit of 0.28 billion €, indicating that our optimization procedure also reduces external N costs at regional scale. This study addresses the old question of whether environmental policies that decrease the societal impact by diluting or concentrating polluting activities are acceptable. Improved algorithms could include additional conditions like that external cost per capita cannot increase anywhere, but this would reduce relocation options. This paper focuses on the supply side solutions. Other solutions from the demand side exploring the benefits associated with a reduction of animal protein in the human diet have been successfully explored in other works like by Westhoek et al. (2014).

Implications for the pork supply chain and circular economy

Our study concludes that currently transport of pigs and pork products contribute only a few percentage points to both the total internal and external costs of pig production, which are dominated by costs related to cultivation of feed cereals and to fattening and breeding of pigs. Only if internal and external cost of (often) road transport would increase substantially in the future, for instance due to increased cost of labour or carbon taxes, this could become a reason to locate pig feed production closer to fattening and breeding facilities. The transport (t × km) of manure and feed cereals could be reduced up to a factor of six. Bringing the pigs in northwestern Europe to the feed cereals, instead of the other way around, also contributes to closure of nutrient cycles and increase of NUE, in accordance with EU ambitions to increase resource efficiency and move to a more circular economy (European Commission 2014b). This provides an additional reason to move a part of the pig production in the south of the Netherlands and in the Flemish region to Northern France, where there is large surplus of feed cereals and a demand for manure (Le Noë et al. 2017). The combined ambition of increasing resource efficiency and circular economy implies a transition to a pig sector more based on regional supply of feed cereals and regional demand for pork.

Barriers for change and possible policy interventions

There is a potential to expand pig production in central and eastern Europe, also to supply pork to northwest Europe. One barrier for this relocation is the necessity of having a complete system for pork production in the region (Larue et al. 2011). For a robust economic performance of a slaughterhouse at least one million pig production units are needed. Substantial investments are also needed to set up new production systems in new EU member states that meet current EU food safety standards. Relocation within a country is expected to meet fewer socio-economic and political barriers and require fewer adaptations of the pig supply chain and transport infrastructure. Equally, policies to enhance implementation of best practices to reduce N excretion and NH_3 losses per pig will meet fewer barriers than policies aimed at relocation. Further barriers for relocation are current considerable differences within the EU of cost of labour, land, energy and capital and also national regulations for environment, spatial planning and established interests of stakeholders. However, on the longer term, towards 2050, these differences are expected to decrease. From the perspective of the advancement of EU economy as a whole and EU ambitions of solidarity and equity, the relocation of pig production in Europe can also be advantageous, but established national economic interests prevent realisation on the short term. EU and national governments could develop policies (e.g. grant schemes, tax benefits, guarantees for investors) encouraging increase of pig production in regions where external costs are low. According to Rogge et al. (2013), major changes, such as relocating parts of the pig sector, have to be accompanied by a shift in policy towards more engagement of stakeholders for the development and implementation of government objectives.

Acknowledgements We thank Max Posch and Jean Paul Hettelingh of the UNECE Coordination Centre for Effects (CCE) for providing European Critical Load data and our PBL colleague Sonja Kruitwagen and Roy Brouwer of University of Waterloo, Canada, for their constructive comments on earlier versions of this manuscript. Luis Lassaletta was partially funded by a Ramon y Cajal grant from MINECO, Spain (RYC-2016-20269)

References

Abdalla CW, Lanyon LE, Hallberg MC (1995) What we know about historical trends in firm location decision and regional shifts: policy issues for industrializing animal sector. Am J Agric Econ 77:1229–1236. https://doi.org/10.2307/1243353

Aramyan LH, Hoste R, van den Broek W, Groot J, Soethoudt H, Nguyen TLT, Hermansen JE, Van der Vorst JG (2011) Towards sustainable food production: a scenario study of the European pork sector. J Chain Netw Sci 11:177–189. https://doi.org/10.3920/JCNS2011.Qpork8

Bateman IJ, Carson RT, Day B, Hanemann M, Hanley N, Hett T, Jones-Lee M, Loomes G, Mourato S, Pearce DW, Sugden R (2002) Economic valuation with stated preference techniques: a manual. Edward Elgar Publishing

Bonneau M, Lebret B (2010) Production systems and influence on eating quality of pork. Meat Sci 84:293–300. https://doi.org/10.1016/j.meatsci.2009.03.013

Brink C, van Grinsven H, Jacobsen BH, Rabl A, Gren I-M, Holland M, Klimont Z, Hicks K, Brouwer R, Dickens R, Willems J, Termansen M, Velthof G, Alkemade R, Van Oorschot M, Webb J (2011) Costs and benefits of nitrogen in the environment. In: Sutton MA, Howard CM, Erisman JW, Billen G, Bleeker A, Grennfelt P, Van Grinsven H, Grizzetti B (eds) The European nitrogen assessment: sources, effects and policy perspectives. Cambridge University Press, Cambridge, pp 513–540. https://doi.org/10.1017/CBO9780511976988.025

Butterbach-Bahl K, Nemitz E, Zaehle S, Billen G, Boeckx P, Erisman JW, Garnier J, Upstill-Goddard R, Kreuzer M, Oenema O, Reis S (2011) Nitrogen as a threat to the European greenhouse gas balance. In: The European nitrogen assessment: sources, effects and policy perspectives. Cambridge University Press, Cambridge, pp 434–462

Desaigues B, Ami D, Bartczak A, Braun-Kohlová M, Chilton S, Czajkowski M, Farreras V, Hunt A, Hutchison M, Jeanrenaud C, Kaderjak P, Máca V, Markiewicz O, Markowska A, Metcalf H, Navrud S, Nielsen JS, Ortiz R, Pellegrini S, Rabl A, Riera R, Scasny M, Stoeckel M-E, Szántó R, Urban J (2011) Economic valuation of air pollution mortality: a 9-country contingent valuation survey of value of a life year (VOLY). Ecol Indic 11:902–910. https://doi.org/10.1016/j.ecolind.2010.12.006

European Commission (2014a) Attitudes of European citizens towards the environment, Special Eurobarometer 416

European Commission (2014b)Towards a circular economy: a zero waste programme for Europe. COM (2014) 398 final

European Commission (2015) Pigmeat market presentations and prices. http://ec.europa.eu/agriculture/pigmeat/presentations/index_en.htm, Accessed 22 Apr 2015

Garnier J, Anglade J, Benoit M, Billen G, Puech T, Ramarson A, Passy P, Silvestre M, Lassaletta L, Trommenschlager JM, Schott C (2016) Reconnecting crop and cattle farming to reduce nitrogen losses to river water of an intensive agricultural catchment (Seine basin, France): past, present and future. Environ Sci Policy 63:76–90. dx.doi.org. https://doi.org/10.1016/j.envsci.2016.04.019

Gerber P, Menzi H (2006) Nitrogen losses from intensive livestock farming systems in Southeast Asia: a review of current trends and mitigation options. In: International Congress Series 1293, Elsevier, Amsterdam pp 253–261

Gren I-M (2008) Costs and benefits from nutrient reductions to the Baltic Sea. The Swedish Environmental Protection Agency, Stockholm https://www.naturvardsverket.se/Documents/publikationer/978-91-620-5877-7.pdf

Grilli ER, Yang MC (1988) Primary commodity prices, manufactured goods prices, and the terms of trade of developing countries: what the long run shows. World Bank Econ Rev 2:1–47

Holland M, Maas R, Jones M, Mills G (2015) Elaboration of the modelling approach for benefits analysis, including illustrative examples. EU 7th Framework Programme Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems (ÉCLAIRE) Deliverable D18.3 http://www.eclaire-fp7.eu/sites/eclaire-fp7.eu/files/eclaire-files/documents/Deliverables/D18_3.pdf

Larue S, Abildtrup J, Schmitt B (2011) Positive and negative agglomeration externalities: arbitration in the pig sector. Spat Econ Anal 6:167–181. https://doi.org/10.1080/17421772.2011.557773

Lassaletta L, Romero E, Billen G, Garnier J, García-Gómez H, Rovira JV (2012) Spatialized N budgets in a large agricultural Mediterranean watershed: high loading and low transfer. Biogeosciences 9:57–70. https://doi.org/10.5194/bg-9-57-2012

Lassaletta L, Billen G, Romero E, Garnier J, Aguilera E (2014) How changes in diet and trade patterns have shaped the N cycle at the national scale: Spain (1961–2009). Reg Environ Chang 14:785–797. https://doi.org/10.1007/s10113-013-0536-1

Le Noë J, Billen G, Lassaletta L, Silvestre M, Garnier J (2016) La place du transport de denrées agricoles dans le cycle biogéochimique de l'azote en France: un aspect de la spécialisation des territoires. Cahiers Agric 25:15004. https://doi.org/10.1051/cagri/2016002

Le Noë J, Billen G, Garnier J (2017) How the structure of agro-food systems shapes nitrogen, phosphorus, and carbon fluxes: the generalized representation of agro-food system applied at the regional scale in France. Sci Total Environ 586:42–55

Lesschen JP, van den Berg M, Westhoek HJ, Witzke HP, Oenema O (2011) Greenhouse gas emission profiles of European livestock sectors. Anim Feed Sci Technol166–167:16–28. doi: https://doi.org/10.1016/j.anifeedsci.2011.04.058

Pearce DW, Turner RK (1990) Economics of natural resources and the environment. Harvester Wheatsheaf, Hemel Hempstead

Posch M, Slootweg J, Hettelingh J-P (eds) (2011) Modelling critical thresholds and temporal changes of geochemistry and vegetation diversity: CCE Status Report 2011. RIVM Report 680359003, Coordination Centre for Effects, Bilthoven, 186 pp www.wge-cce.org

Rabinowitz P, Conti L (2013) Links among human health, animal health, and ecosystem health. Annu Rev Public Health 34:189–204. https://doi.org/10.1146/annurev-publhealth-031912-114426

Roe B, Irwin EG, Sharp JS (2002) Pigs in space: modelling the spatial structure of hog production in traditional and non-traditional production regions. Am J Agric Econ 84:259–278

Rogge E, Dessein J, Verhoeve A (2013) The organisation of complexity: a set of five components to organise the social interface of rural policy making. Land Use Policy 35:329–340. https://doi.org/10.1016/j.landusepol.2013.06.006

Sutton MA, Bleeker A, Howard CM, Bekunda M, Grizzetti B, De Vries W, Van Grinsven HJ, Abrol YP, Adhya TK, Billen G, Davidson EA (2013) Our nutrient world: the challenge to produce more food and energy with less pollution, Edinburgh, Centre for Ecology & Hydrology on behalf of the Global Partnership on Nutrient

Management (GPNM) and the International Nitrogen Initiative (INI)

Trienekens JH, Wognum PM (2009) Introduction to the European pork chain. In: European pork chains: diversity and quality challenges in consumer-oriented production and distribution. Wageningen Academic Publishers, Wageningen, pp 19–36

Tully SM, Winer RS (2014) The role of the beneficiary in willingness to pay for socially responsible products: a meta-analysis. J Retail 90:255–274. https://doi.org/10.1016/j.jretai.2014.03.004

Van Grinsven HJM (2016) Putting an economic value on nitrogen pollution in Europe: can we improve the unit N cost method using results of the Eurobarometer? Proceedings of the 2016 International Nitrogen Initiative Conference, "Solutions to improve nitrogen use efficiency for the world", 4–8 December 2016, Melbourne http://www.ini2016.com/wp-content/uploads/2016/03/INI2016_Vangrinsven_Hans.pdf

Van Grinsven HJM, Holland M, Jacobsen BH, Klimont Z, Sutton MA, Willems J (2013) Costs and benefits of nitrogen for Europe and implications for mitigation. Environ Sci Technol 47:3571–3579. https://doi.org/10.1021/es303804g

Van Grinsven HJM, Spiertz J, Westhoek H, Bouwman A, Erisman J (2014) Nitrogen use and food production in European regions from a global perspective. J Agric Sci 152:9–19. https://doi.org/10.1017/S0021859613000853

Velthof G, Oudendag D, Witzke HP, Asman WAH, Klimont Z, Oenema O (2009) Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. J Environ Qual 38:402–417. https://doi.org/10.2134/jeq2008.0108

Westhoek H, Rood T, Van den Berg M, Janse J, Nijdam D, Reudink M, Stehfest E (2011) The protein puzzle—the consumption of meat, dairy and fish in the European Union. PBL Environmental Assessment Agency, Bilthoven

Westhoek H, Lesschen JP, Rood T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton MA, Oenema O (2014) Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Glob Environ Chang 26:196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004

Willems J, van Grinsven HJM, Jacobsen BH, Jensen T, Dalgaard T, Westhoek HW, Kristensen IS (2016) Why Danish pig farms have far more land and pigs than Dutch farms? Implications for feed supply, manure recycling and production costs. Agric Syst 144:122–132. https://doi.org/10.1016/j.agsy.2016.02.002

Winkler T, Schopf K, Aschemann R, Winiwarter W (2016) From farm to fork—a life cycle assessment of fresh Austrian pork. J Clean Prod 116:81–88. https://doi.org/10.1016/j.jclepro.2016.01.005

Wossink A, Wefering F (2003) Hot spots in animal agriculture, emerging federal environmental policies and the potential for efficiency and innovation offsets. Int J Agric Resour Gov Ecol 2:228–242. https://doi.org/10.1504/IJARGE.2003.003970