Safeguarding Natura 2000 habitats from nitrogen deposition by tackling ammonia emissions from livestock facilities

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Abstract

Nitrogen deposition is one of the main environmental threats to the conservation goals in areas protected by the European Habitats Directive, a problem that is quite pronounced in the livestock-rich region of Flanders, Belgium. Livestock farms are often located close to Natura 2000 areas. Therefore, ammonia emissions from livestock housing and manure storage have a high contribution to the deposition in these nearby protected habitats. In order to control this problem, the Flemish government imposes restrictions on livestock farms with a high impact on protected habitats. Using an integrated spatially-explicit modeling approach, we were able to show that the effectiveness of this spatially-differentiated policy is rather limited in terms of the percentage of habitats in exceedance of the critical load for nitrogen. In order to obtain a good status in all habitats, emission abatement efforts should extend beyond the livestock sector. Furthermore, the policy affects some livestock subsectors more than others, while similar discrepancies are unveiled on the level of different habitat types. By means of 4 different habitat classes, the effectiveness of different policy scenarios can be easily assessed on the level of individual habitats.

Keywords

Ammonia, Livestock, Nitrogen Deposition, Habitats Directive, Natura 2000

1. Introduction

The emission of nitrogen oxides (NO_x) and ammonia (NH_3) to the air contributes to eutrophication, due to deposition of these reactive nitrogen compounds on soils, vegetation and surface waters (European Environment Agency, 2018a). The sensitivity of ecosystems to this process of atmospheric nitrogen deposition is reflected through the critical load, the amount of nitrogen an ecosystem can maximally absorb without negative effects (European Environment Agency, 2018a). In 2016, the critical load for eutrophication was exceeded in 73% of the ecosystem area in the EU28 (EMEP, 2018). Nitrogen deposition is one of the major threats to the Natura 2000 network, the pan-European network of protected sites aimed at conserving or restoring threatened and endangered species and habitats, established by the European Habitats Directive (Schoukens, 2017). Article 6 of the Habitats Directive imposes member states to avoid further deterioration of habitats and additional adverse impacts, which puts a limit to permitting additional nitrogen emissions in the vicinity of Natura 2000 sites (Schoukens, 2018).

Among the economic activities most affected by this legislative requirement is agriculture: it contributes 92% of the total NH_3 emission in the EU (European Environment Agency, 2018a), while farms often have a relatively high impact on neighboring natural sites because of the fact that most of the emitted NH_3 is deposited close to the emission source (Loubet et al., 2009). The livestock sector has a share of 82% of the total agricultural NH_3 emission (Leip et al., 2015). Emissions from animal housing and manure storage can be considered as point sources, in contrast to diffuse emissions coming from manure spreading and grazing (Carnell et al., 2017). Due to the high spatial variability of the NH_3 concentration and deposition (Vogt et al., 2013), spatially-targeted emission abatement is a favorable policy strategy to alleviate ammonia deposition in Natura 2000 areas (Dragosits et al., 2006; Hicks et al., 2011).

In accordance with Article 6 of the Habitats Directive and in order to improve the conservation status of Natura 2000 habitats and species, European member states have to take action to alleviate the problem of nitrogen deposition. Among the regions in Europe with the highest amount of nitrogen deposition are Denmark (Ellermann et al., 2018), the Netherlands (Kros et al., 2013), the German state of Lower Saxony (Wagner et al., 2017) and the Belgian region of Flanders (De Pue et al., 2017), each characterized by a high density of livestock. In the Netherlands, the national government came up with the Programmatic Approach to Nitrogen (Bouwma et al., 2018). The goal of this integrated policy program is to ensure that the European nature objectives are achieved, while at the same time leaving room for economic development (Luesink and Michels, 2018). General emission abatement and site-specific management and restoration measures create room for deposition, which can be used to permit livestock farms (Luesink and Michels, 2018; Schoukens, 2017). Flanders, the region of Belgium that neighbors the Netherlands to the south, came up with its own Programmatic Approach to Nitrogen, which includes specific restrictions to farms that contribute a high share of the nitrogen deposition in relation to the critical load. The policy targets agricultural point emissions from animal housing and manure storage. If the nitrogen deposition attributable to a farm amounts to more than 50% of the critical load in a habitat, it cannot acquire a permit, while farms contributing 5 to 50% of the critical load can only be licensed under specific conditions, such as a guarantee that the NH_3 emission doesn't increase (De Pue et al., 2017).

In this study, we evaluated the effectiveness and efficiency of this spatially-differentiated policy on the level of individual farms and habitats in Flanders, using a spatially-explicit integrated modeling approach described by De Pue et al. (2019). Furthermore, we simulated two additional scenarios that are more effective in regard to deposition in protected habitats. Our model allows to compare the emission abatement efforts between different livestock subsectors, and the effects on different habitat types protected within the Flemish Natura 2000 network, revealing disparities on these two levels. While the model reported by De Pue et al. (2019) enabled simulating emission abatement measures of individual stables in a spatially-explicit way, the extension of the model presented in this paper allows studying the effectivity of different policy scenarios on the level of different Natura 2000 areas, habitat types and even individual receptors.

2. Methodology

2.1 Research approach and scope

Our analysis is focused on the region of Flanders, Belgium, looking at ammonia emission from livestock housing and its impact on protected Natura 2000 areas through deposition. Our optimization model integrates data on 23408 livestock farms and 71787 hectares of protected habitats within the Natura 2000 network (habitats that are currently present, De Saeger et al., 2016), divided over 38 Special Areas of Conservation. The economic-ecological mixed-integer linear programming (MIP) modeling approach was described in detail by De Pue et al., 2019 (submitted manuscript, available on request). The model optimizes the total economic benefit for the livestock sector in Flanders, while at the same time complying with predefined environmental targets regarding deposition in protected areas. Farms can consist of multiple stables. On the level of individual stables, the model integrates information on the type of animals, the maximum number of animals, and the current stable types. The model decides on the stable type, optional additional emission abatement techniques, and the number of animals, which determines the ammonia emission and the abatement cost. To decrease the emission of a farm, the model can choose between technical emission abatement (low-ammonia emission stable type, air scrubbers, etc.), a reduction of output (animal numbers), or a combination thereof. On the farm level, the net revenue for the farm is calculated, taking into account the gross margin per animal category and the abatement costs for all the stables. The impact on neighboring Natura 2000 sites is also calculated on farm level, by integrating atmospheric dispersion modeling with information on the sensitivity of the habitat types (De Pue et al., 2017), reflected in the critical load for nitrogen (Ferm, 1998; Krupa, 2003). This critical load is defined as a level of nitrogen deposition (expressed in kilograms of nitrogen per hectare per year), below which no significant harmful effects are expected according to current knowledge. Lastly, on the regional level of Flanders, the aggregated emission, impact and revenue is calculated. The model in the current paper differs from the one described in De Pue et al., 2019 in that respect that it allows to study and visualize the impact in each hectare of protected land, instead of merely evaluating the impact on an aggregated scale through the Aggregate Deposition Score (De Pue et al., 2019, 2017). Furthermore, it allows to include scenarios where a good status of all habitats is a prerequisite (see below).

2.2 Habitat class

In order to evaluate the effectivity of the different policy scenarios on the level of all hectares of protected habitat, we introduce the concept of habitat class, a color code that reflects the state of the habitat and the adequacy of the livestock emission reduction. The habitat class assignment is done for each of the 71787 hectares of protected habitat and is based on the relation between the total nitrogen deposition in the habitat before emission reduction, the critical load of the habitat and the deposition attributable to local livestock before and after emission reduction (Table 1). Whether a reduction of ammonia emission in local livestock facilities is sufficient to get below the critical load is greatly dependent on the average deposition attributable to local livestock. It is important to note that local livestock is not the only sector contributing to nitrogen deposition in Natura 2000 areas, and that a sizeable share of the deposition can be attributed to reactive nitrogen imported from abroad (Lefebvre and Deutsch, 2015). The conditions for assigning all the habitats to different classes are outlined in Table 1. The total deposition after emission reduction can either be above or below the critical load. If the total deposition is below the critical load even without emission reduction, we assign the class 'blue' to the habitat. If it gets below the critical load due to emission reduction, we assign the class 'green'. For habitats that are still in exceedance of the critical load, even after emission reduction, the color assignments depend on the relative decrease of the deposition attributable to local livestock facilities. If the reduction is proportionate to the required reduction to get below the critical load if all contributing sectors do a similar effort, meaning that the ratio of the local deposition in the scenario to the local deposition in the reference is smaller than the ratio of the critical load to the total deposition in the reference, the class 'yellow' is assigned. If the last condition is not fulfilled, it means that the reduction is insufficient to get below the critical load even if all sectors do a similar effort as the local livestock facilities, in which case the class 'red' is assigned.

Table 1: Habitat classes. TND_{ref}: Total Nitrogen Deposition in reference scenario. $TND_{scenario}$: Total Nitrogen Deposition after policy implementation. CL: critical load for nitrogen deposition. LND_{ref}: Deposition attributable to local livestock housing in reference scenario. $LND_{scenario}$: Deposition attributable to local livestock housing after policy implementation.

Habitat Class	Description	Condition
(blue)	Critical load not exceeded even without emission reduction	$TND_{ref} < CL$
(green)	Critical load no longer exceeded after policy implementation	$TND_{ref} >= CL$ AND $TND_{scenario} < CL$
(orange)	Exceedance of critical load, reduction of deposition attributable to local livestock is sufficient.	$TND_{ref} >= CL$ AND $TND_{scenario} >= CL$ AND $LND_{scenario}/LND_{ref} < CL/TND_{ref}$
(red)	Exceedance of critical load, reduction of deposition attributable to local livestock is unsufficient.	$LND_{ref} >= CL$ AND $LND_{scenario} >= CL$ AND $LND_{scenario}/LND_{ref} >= CL/TND_{ref}$

2.3 Scenarios

We modeled a total of 4 scenarios. In the **Full Capacity (FC)** scenario, we assume that all livestock exploitations are at their maximum capacity (maximally permitted animal numbers for the year 2015, De Pue et al., 2019). As there is no environmental target imposed on the model, this scenario provides the reference situation without any additional emission abatement. The scenario **Current Policy (CP)** aims to simulate the current spatially-differentiated measures embedded within the Flemish Programmatic Approach to Nitrogen, which is to limit the individual contribution of livestock exploitations to maximum 5% of the critical load in each of the habitats they affect. In the **Spatial Optimization (SO)** scenario, there are no individual constraints on the exploitations, but the overall impact on Natura 2000 sites is minimized while the overall abatement costs for all farms combined should be in the same range as in the CP scenario. Lastly, the most strict scenario is the **Proportionate Reduction (PR)** scenario, where we impose that, in all habitats, the percent reduction of the part of deposition originating from neighboring livestock facilities should be at least sufficient to get below the critical load. In other words, none of the protected habitats is allowed to be of the 'red' habitat class. In addition to the aforementioned scenarios, we also simulated two series of scenarios in which a gradual reduction in respectively the total ammonia emission and the total impact is imposed, ranging from -10% to -60%, in steps of 10%. These gradual reduction scenarios reveal the marginal abatement cost for both ammonia emission reduction and impact (Aggregate Deposition Score) reduction, reported as shadow prices for the respectively the regional emission constraint and the regional impact constraint.

3. Results

3.1 Regional results

The model generates results on different levels, including on the level of individual emission sources, protected habitats and municipalities. Here, we only show the results that we deem to be most relevant to our story. Table S1 in the Supplementary material lists the main outputs generated by the model. Specific results can be obtained from the authors upon request. Table 1 shows the main results on the regional level. Limiting the significance score of each of the 23408 farms to 5% results in a reduction of the total deposition impact of 24%, with a reduction in the total benefit of just 2.8% (total abatement cost of 33.9 million euros). The percentage of habitats with an exceedance of the critical load for nitrogen decreases from 56.2% in the Full Capacity case to 49.9% in the CP scenario, with 27.4% of the habitats in an unfavorable condition (Figure 1, lower panel). In the spatial optimization scenario, the percentage of habitats with an exceedance of the critical load is further reduced to 42.5%, with 6.5% of the habitats in an unfavorable condition (Figure 1, lower panel). In the Proportionate Reduction scenario, the critical load exceedance is similar to the SO scenario, but almost all habitats are in a favorable state, which was a prerequisite environmental target in this scenario. The reason that there are still 0.1% of habitats in an unfavorable state is due to the fact that in mixed integer programming, the solver doesn't succeed in finding the exact optimum. Obtaining the strict environmental target comes at a considerable cost: the total abatement cost in the PR scenario amounts to 173.7 million euros, over five times as much as in the Current Policy scenario. Furthermore, over 15% of the farms are closed in this scenario.

Table 1: Main results on regional level

	FC	CP	SO	PR
Total NH_3 emission (kton yr^{-1})	35.7	33.0	25.1	18.7
Total Impact (Σ ADS)	15667	11867	7391	6395
Number of closed stables	0	649	3681	8912
Number of closed farms	0	111	1438	3547
Total benefit (billion €)	1.230	1.196	1.191	1.056
Total abatement cost (million €)	0	33.9	38.5	173.7
Critical Load exceedance (%)	56.2	49.9	42.5	42.3
Habitat Class Red (%) (>CL, reduction insufficient)	56.2	27.4	6.5	0.1

Looking at the deposition in individual habitats allows to evaluate the effectiveness of the policy on a detailed level. In the left panel of Figure 1, a histogram of all protected hectares is shown for the 4 scenarios, with the critical load exceedance (kg N ha^{-1} yr^{-1}) on the horizontal axis. To obtain the figure, for each of the habitats, the critical load of the habitat was subtracted from the total nitrogen deposition in the habitat. In the habitats to the right of the dashed line, the critical load is exceeded. Going from the Full Capacity (FC) scenario to the most strict Proportionate Reduction (PR) scenario, there's a shift visible to the left, towards lower critical load exceedance. However, it's also immediately apparent that targeting local livestock housing facilities only has a limited effect on the habitats. As described above, the total percentage of habitats in exceedance of the critical load decreases from 56% in the Full Capacity scenario to 42% in the Spatial Optimization and Proportionate Reduction scenarios. In the last two scenario's, the large peak of protected habitats that is characterized by a critical load exceedance of a few kg N ha^{-1} yr^{-1} is shifted to the left of the critical load, which means that the critical load is no longer exceeded in those habitats. For the large proportion of habitats where the critical load is still exceeded in the 3 alternative scenarios, we make the distinction between habitats where the reduction in deposition attributable to local livestock housing is sufficient (habitat class yellow) if other contributing sectors would contribute equally to the reduction of impact, versus the habitats where this is not the case (habitat class red). The right panel of Figure 1 reveals that in terms of habitat class, the difference between the SO and PR scenarios is limited to the 6.5% of habitats where the reduction of deposition attributable to local livestock housing facilities is insufficient.

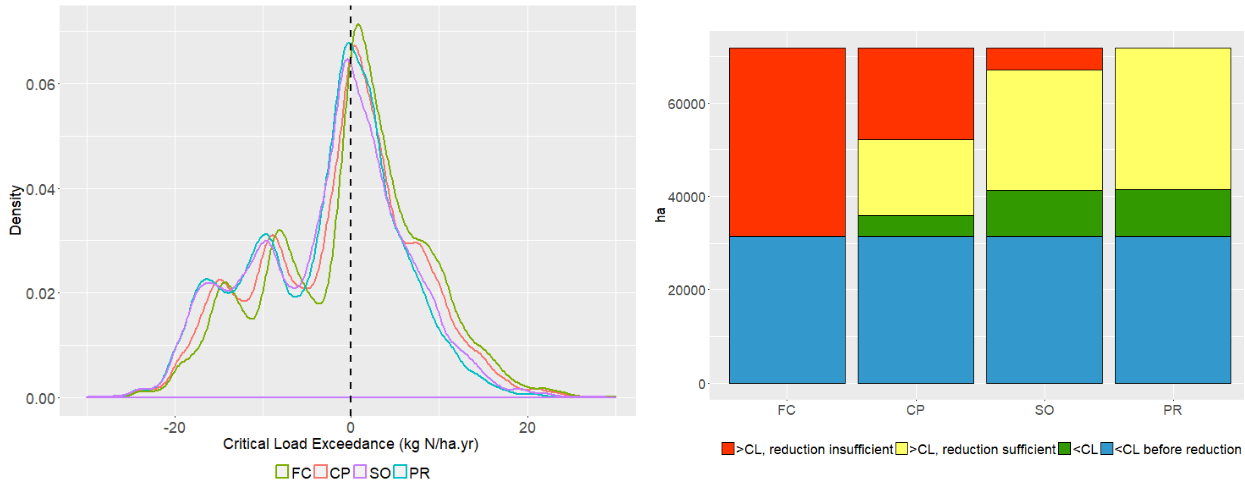

__Figure 1: Effectiveness of spatially-differentiated measures to abate ammonia deposition in natural areas. Left panel__: Absolute exceedance of the critical load for nitrogen. __Right panel__: Distribution of habitat classes. FC: Full Capacity. CP: Current Policy. SO: Spatial Optimization. PR: Proportionate Reduction.

3.2 Abatement costs on sectoral level

The emission abatement costs can be split according to type (technical abatement versus reduction in animal numbers) and according to sector. In Figure 2, the abatement costs are shown for the 3 main sectors (cattle, pigs and poultry), revealing differences in abatement efforts. The Current Policy scenario relies predominantly on output reduction, with the cattle sector having the highest abatement cost (15,4 million euros, 97% of which is due to animal reduction). In the Spatial Optimization scenario, the main abatement effort is carried by the pig sector (23,3 million euros), with technical abatement measures dominating over output reduction (76% versus 24%). As already shown in Table 1, the Proportionate Reduction scenario is substantially more expensive than the other scenarios, with a total abatement cost of 173,7 million euros, with the pig sector carrying over half of the total cost. For each of the 3 main sectors, animal reduction is the main cost in this scenario.

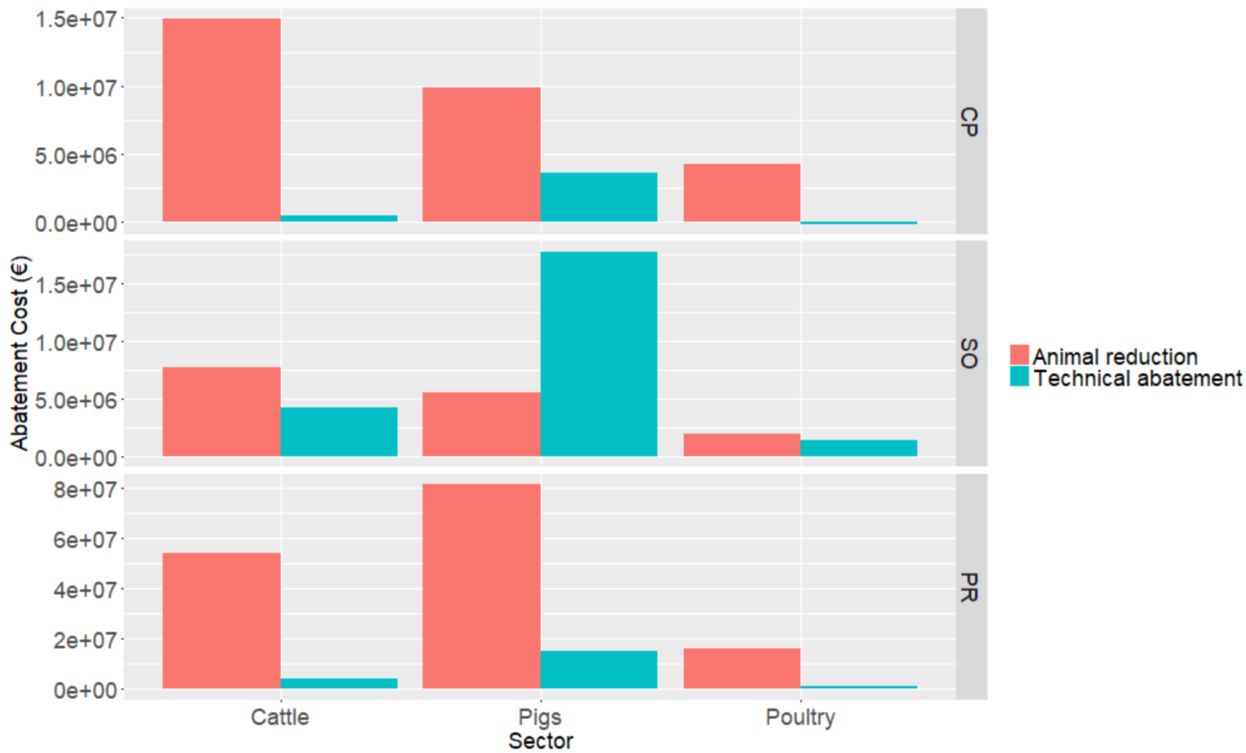

Figure 2: Emission abatement costs for the 3 main livestock sectors. *CP: Current Policy. SO: Spatial Optimization. PR: Proportionate Reduction. Note the different scale on the vertical axis for scenario PR.*

3.3 Habitat level results

The distribution of protected hectares according to habitat class, as shown in the right panel of Figure 1 for all habitats together, can also be shown for all 42 habitat types that occur in Flanders separately (Supplementary Figure 1), which allows assessing the status of each of the habitat types in detail. Alternatively, the habitats can be shown on the map (Figure 3). The upper left corner shows the starting situation (Full Capacity), with habitats that are either in exceedance of the critical load (red) or below the critical load (blue). In the Current Policy scenario, some of the red habitats are converted to a more favorable class, but there's still a substantial portion of habitats where the deposition reduction is insufficient. In the Spatial Optimization scenario, the situation improves greatly in the East of Flanders, where habitats are clustered in bigger Natura 2000 areas, compared to smaller Natura 2000 areas in the West of Flanders, where there's still a big proportion of habitats with an unfavorable class. As imposed by the model, in the Proportionate Reduction scenario, there are no habitats with habitat class red.

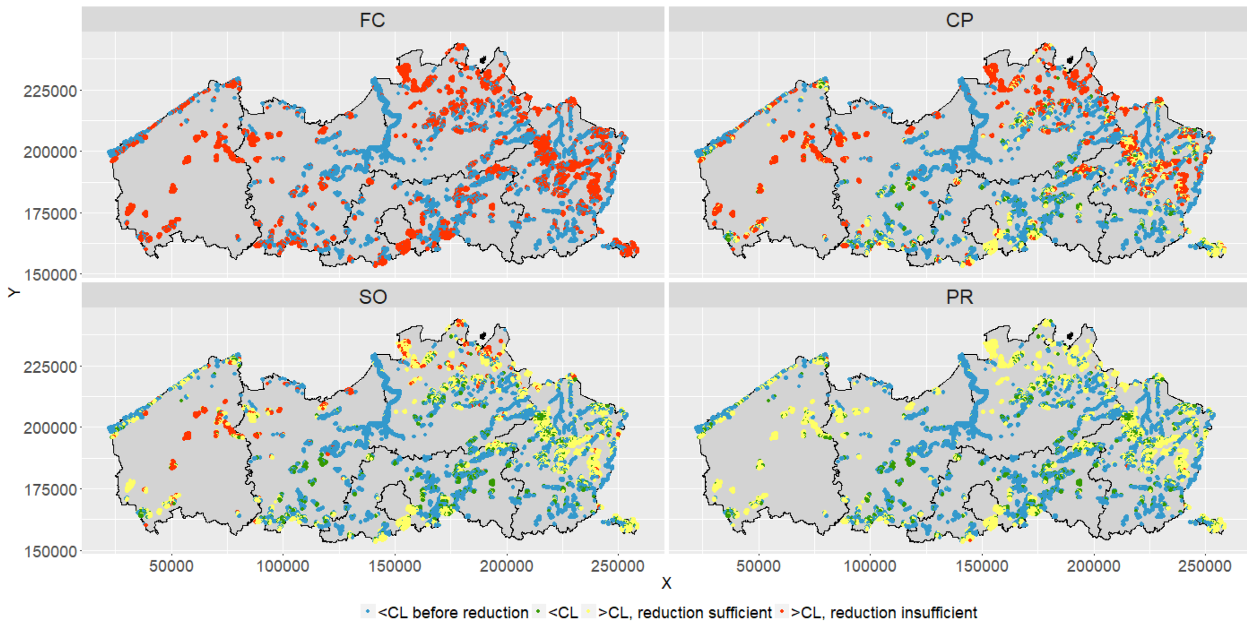

Figure 3: Location of protected habitats in Flanders, colored according to habitat class. *FC: Full Capacity. CP: Current Policy. SO: Spatial Optimization. PR: Proportionate Reduction.*

The emission abatement costs can also be allocated to all protected habitats. The principle of the cost allocation is outlined in Supplementary Table 2. In Figure 4, the allocated costs are shown in function of the total deposition for 3 habitat types, each characterized by a different critical load. The position of the critical load is indicated by the dashed line, while the habitat class of all habitats is also shown. By definition, habitats to the left of this line are colored green or blue, while the ones to the right are yellow or red (see Section 2.2 for the definition of the 4 habitat classes). It’s clear that even for 1 habitat type, the costs allocated to different hectares varies greatly, though there’s no clear correlation with the total nitrogen deposition in those habitats. Furthermore, the Proportionate Reduction scenario is by far the most expensive (note the different scale on the vertical axis). For the most sensitive habitat type shown in Figure 4, habitat 2330 (Inland dunes with open *Corynephorus* and *Agrostis* grassland), only 2 hectares are below the critical load. The allocated costs for each hectare of protected habitat can be compared to costs made for habitat restoration measures in those protected habitats, which enables comparing the efforts by farmers to reduce emissions versus the efforts of conservationists to restore the habitat.

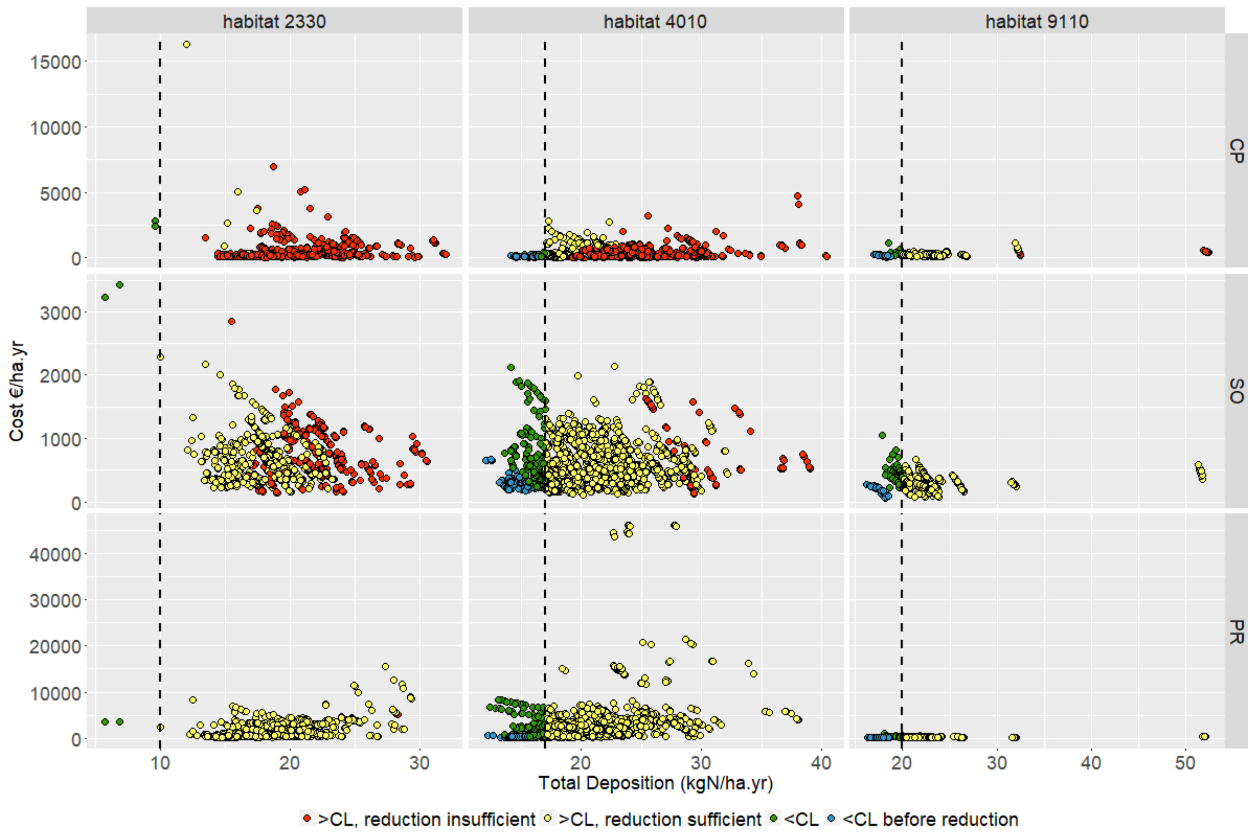

Figure 4: Emission abatement costs allocated to single habitats, colored according to habitat class. *The dashed line shows the position of the critical load. Habitat 2330: Inland dunes with open Corynephorus and Agrostis grassland, Critical load 10 kg N* ha^{-1} yr^{-1}*. Habitat 4010: Northern Atlantic wet heaths with Erica tetralix, Critical load 17 kg N* ha^{-1} yr^{-1} *. Habitat 9110: Luzulo-Fagetum beech forests, Critical load 20 kg N* ha^{-1} yr^{-1}*. FC: Full Capacity. CP: Current Policy. SO: Spatial Optimization. PR: Proportionate Reduction. Note the different scales on the vertical axis, according to the different scenarios.*

3.4 Gradual reduction scenarios

In the upper panel of Figure 5, the total abatement costs in function of the reduction of respectively the total NH_3 emission and total impact are shown. For each percentage reduction, reducing the emission proves to be more expensive than reducing the impact. This is expected, as the most cost-efficient reduction in impact can be obtained by spatially targeting the emissions coming from sources with a high impact. A reduction in emissions in these high-impact locations results in a relatively larger reduction in impact. The emission abatement costs can also be shown for each of the main livestock sectors (Figure 5, lower panel), split according to the type of abatement (technical abatement versus output reduction). For cattle, the technical abatement costs and the cost of animal reduction are within the same range for a reduction of up to 30% of the impact or the emission. For bigger reductions, both types of costs start to deviate, with the impact reduction scenarios having a higher cost due to output reduction, and the emission reduction scenarios having a higher cost due to technical abatement, with the exception of the 60% ammonia reduction scenario, in which the cost due to animal reduction becomes higher than the technical abatement cost. For the pig sector, the technical abatement cost dominates over the animal reduction costs in both the impact and emission reduction scenarios. For poultry, the technical abatement costs are negative for the smaller reduction scenarios (up until -20% impact and -10% emission), and only become positive for higher reduction scenarios. While the technical abatement costs and animal reduction costs for the poultry sector are similar for the gradual reduction in impact, apart from a small deviation for higher reduction percentages, in the emission reduction scenario, the technical abatement costs have the upper hand over the animal reduction costs, with the exception of the lowest (-10%) and highest (-60%) reduction scenarios.

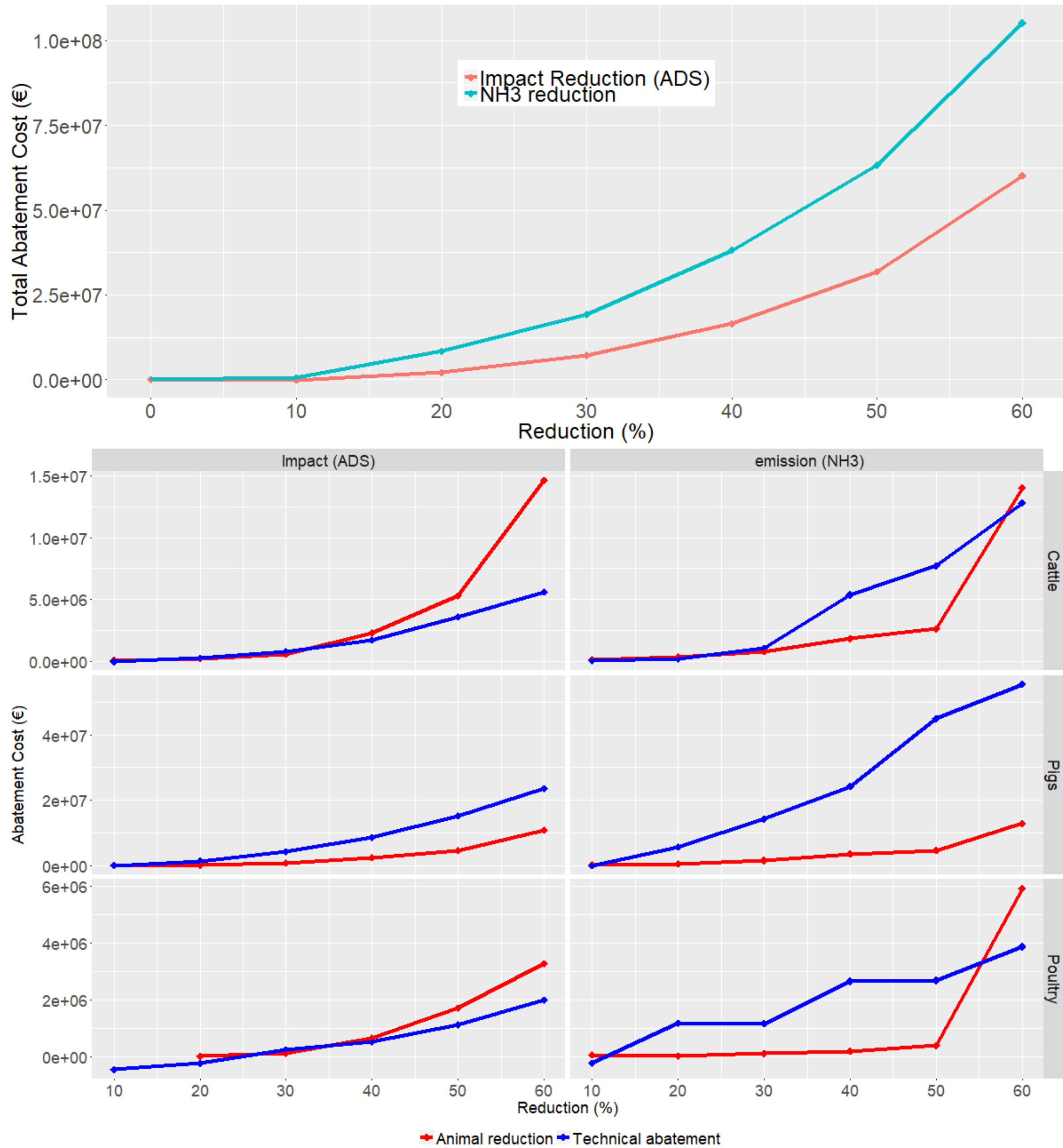

Figure 5: Emission abatement costs in gradual reduction scenarios. Upper panel: *Total abatement costs for emission reduction and impact reduction scenarios.* ***Lower panel:*** *Emission abatement costs split per livestock sector.*

The marginal abatement costs, derived from the shadow prices of the overall impact and emission constraints in the gradual reduction scenarios, are shown in Table 1, highlighting the rising marginal abatement costs in function of reduction target. The marginal abatement cost for reducing the regional ammonia emissions rises from 1.74 € per kg NH_3 in case of a 10% reduction to 17.20 € per kg NH_3 in case of a 60% reduction, while the marginal abatement cost for reducing the impact rises from 1482.82€ per ADS point for a 10% reduction to 24261.19€ per ADS point for a 60% reduction.

Table 1: Marginal abatement costs for ammonia reduction and impact reduction.

	10%	20%	30%	40%	50%	60%
Marginal abatement cost NH_3 reduction (€/kg NH_3)	1.74	2.57	4.12	6.60	8.10	17.20
Marginal abatement cost impact reduction (€/ADS)	1482.82	2625.40	4148.51	8665.58	13428.50	24261.19

4. Discussion

4.1 Meeting the target of non-exceedance of critical loads

By using integrated economic-ecological modelling, we were able to study the impact of different scenarios aimed at decreasing the impact of agricultural point emissions of ammonia (animal housing and manure storage) on habitats protected by the Habitats directive in Flanders. The regional results shown in Table 1 reveal the limited effectiveness of the current Flemish policy (CP), which succeeds in decreasing the critical load exceedance from 56,2% to 49,9%, at an emission abatement cost of 33,9 million euros per year. It's important to note that the CP scenario we simulated is stricter than the Flemish policy, as the policy allows, under certain restrictions, the licensing of farms that contribute between 5-50% of the critical load in a protected habitat (De Pue et al., 2017). The effectiveness we predict here is therefore an overestimation. In the alternative spatially optimal scenario (SO), the critical load exceedance drops to 42.5%, at a higher costs of 5 million euros per year compared to the current policy scenario. However, in order to obtain a favorable status in all habitats (scenario PR), the abatement costs rise to 173,7 million euros per year, with a critical load exceedance that is only slightly better than in the SO scenario (42,3%).

Meeting the EU's long term objective of not exceeding critical loads of eutrophying substances in all ecosystem areas (European Environment Agency, 2018a) will not only entail high abatement costs to livestock farmers in Flanders, it will also require other nitrogen-emitting sectors to further contribute to the reduction in deposition. However, the nitrogen oxide emissions from transport, industry and energy in the EU have declined considerably more than ammonia emissions from agriculture (European Environment Agency, 2018a). In the EU28, the overall emissions of NO_x have declined by 58% between 1990 and 2016, while the emissions of NH_3 declined by only 23% (European Environment Agency, 2018b). Reduced nitrogen is already the dominant contributor to eutrophying deposition in Flanders: of the total nitrogen deposition in Flanders in 2017, 59% consisted of reduced nitrogen (NH_x), 32% of oxidized nitrogen (NO_x) and 8% of dissolved organic nitrogen (Vlaamse Milieumaatschappij, 2018). Furthermore, 46% of the nitrogen deposition is attributable to sources outside Flanders (Vlaanderen Departement Omgeving, 2018), indicating that a pan-European effort in reducing the emissions of reactive nitrogen compounds is needed. Likewise, with Flanders exporting three times as much nitrogen deposition than it imports (Vlaanderen Departement Omgeving, 2018), reductions in Flemish emissions will also contribute to ecosystem improvement in neighboring countries.

In any case, the current ambition levels regarding emission reduction, as outlined in the EU National Emission Ceilings Directive (2016/2284/EU), will not suffice to allow the recovery of ecosystems (Dirnböck et al., 2018). Recently, question rose up about the adequacy of critical loads as ecologically-meaningful indicators of nitrogen deposition (Payne et al., 2019). The main issue is that ecosystems recover slowly of the effects of nitrogen deposition, even when the critical load is no longer exceeded (Stevens, 2016). As an alternative to the critical load, Payne et al. (2019) propose the cumulative deposition over a thirty-year window as metric for the ecological damage of nitrogen deposition. Even if the EU objective of non-exceedance of critical loads will be met in 2050, the deleterious effects of nitrogen deposition will likely linger on even further in the future.

4.2 Quantifying the emission abatement effort

Looking at the emission abatement efforts for the main livestock sectors (Figure 2), substantial differences in total level and type of emission abatement costs appear, due to differences in profitability (cost of output reduction), options for technical abatement, and impact of farms due to distance to natural areas, as already discussed by De Pue et al., 2019. The Habitats Directive is often perceived to have initiated a clash between nature conservation and economic activities (Ferranti et al., 2019). Our work supplies figures to the discussion: by allocating the emission abatement costs to individual hectares of protected habitat (Figure 4), we can compare the costs made by livestock farmers to the costs of restoration strategies aimed at mitigating the effects of atmospheric nitrogen deposition, such as topsoil removal, mowing and extensive grazing (De Keersmaeker et al., 2018).

Furthermore, the gradual reduction scenarios (section 3.4) reveal the increasing marginal abatement costs, both for reducing the total ammonia emission and the total impact on Natura 2000 habitats. The cost per kg of NH_3 per year reduced raises from 1,74 €/kgN in the 10% reduction scenario to 17,20 €/kgN in the 60% reduction scenario. Similar marginal cost curves for NH_3 mitigation were revealed earlier for the whole of Europe (Brink et al., 2011). From a classic environmental-economical point of view, the optimal level of emission abatement is the point at which the marginal abatement cost equates the marginal damage cost, which is also applicable to nitrogen pollution (van Grinsven et al., 2018). Van Grinsven et al. (2013) estimated the cost of ammonia emissions to human health in the EU (through the formation of secondary particulate matter) to be 12€/kg NH_3 emitted, and the cost to ecosystems to be 2€/kg NH_3 emitted, indicating that health costs outweigh costs due to ecosystem damage. If we neglect the considerable uncertainty on these estimates (van Grinsven et al., 2013), sticking to the rule that the mitigation effort should equate the damage cost would mean that the total ammonia emission by livestock housing and manure storage in Flanders should be reduced by more than 50% (see Table 2). This reduction requirement would, of course, change when new, cost-efficient emission abatement measures would become available (lowering the marginal abatement cost), or when the profitability of livestock farming would go up (increasing the cost of animal reduction) or down (decreasing the cost of animal reduction). The adequacy of a uniform ecosystem damage cost for ammonia has recently been challenged: Jones et al., 2018 pointed out that the marginal benefit of lowering nitrogen deposition in habitats tends to be higher at lower nitrogen deposition levels. In other words, a unit change in N deposition has greater value at lower nitrogen deposition, because the environmental gain in terms of species richness is bigger at lower levels of deposition (Jones et al., 2018). Furthermore, the highly heterogeneous spatial pattern of the economic benefits related to a reduction in nitrogen deposition invigorates the call for spatially-differentiated pollution control.

4.3 Pathways for future research

In this study, we developed a spatially-explicit methodology to link efforts to reduce point source emissions of livestock (animal housing and manure storage), either by technical abatement measures or by output reduction, with the effect of these efforts on habitats protected within the Natura 2000 network. The concept of the habitat class, a color code reflecting the state of the habitat and the adequacy of livestock ammonia emission reduction, can be used for a straightforward assessment of the effect of different policy scenarios on habitats, either for all protected habitats together (Figure 1, right panel), shown on a map (Figure 3), or as 'dashboard' of all the different habitat types (Supplementary Figure 1). For example, the relative advantage of spatially-differentiated measures (restricting emission in areas with a high impact on Natura 2000 habitats) versus generic measures (imposing similar emission reduction targets for all farms, or imposing technology standards by obliging the adoption of best available techniques), can be evaluated on the level of individual habitats in an intuitive manner.

Using region-specific input data (habitat maps, source-receptor matrices, farm census data), the methodology applied here can be transferred to other regions or countries in Europe. When these region-specific data are integrated on the European level, the model can shed light on transboundary nitrogen deposition. Another pathway for future research is extending the model by integrating other ammonia-emitting steps of the manure chain (Hou et al., 2016) beside the point source emissions (grazing, manure spreading), and additional emission control options such as dietary measures (Loyon et al., 2016). Lastly, a similar spatially-explicit modeling approach can be applied to evaluating policies aimed at other pollution problems characterized by spatial heterogeneity in emissions and impact, such as nitrate pollution in water catchments (Hashemi et al., 2018).

5. Conclusion

The results of this study indicate that the current spatially-differentiated policy to abate ammonia emissions from livestock housing and manure storage in Flanders is insufficient to meet the long-term target of non-exceedance of the critical load for nitrogen deposition in all Flemish Natura 2000 areas. Moreover, differences in abatement costs between farms and sectors and differences in effectivity in terms of nitrogen deposition in protected habitats were revealed. Lastly, the here proposed allocation of habitats according to 4 different classes, allows to quickly assess the effectiveness of different policy scenarios on the level of individual habitats, habitat types and Natura 2000 areas.

6. References

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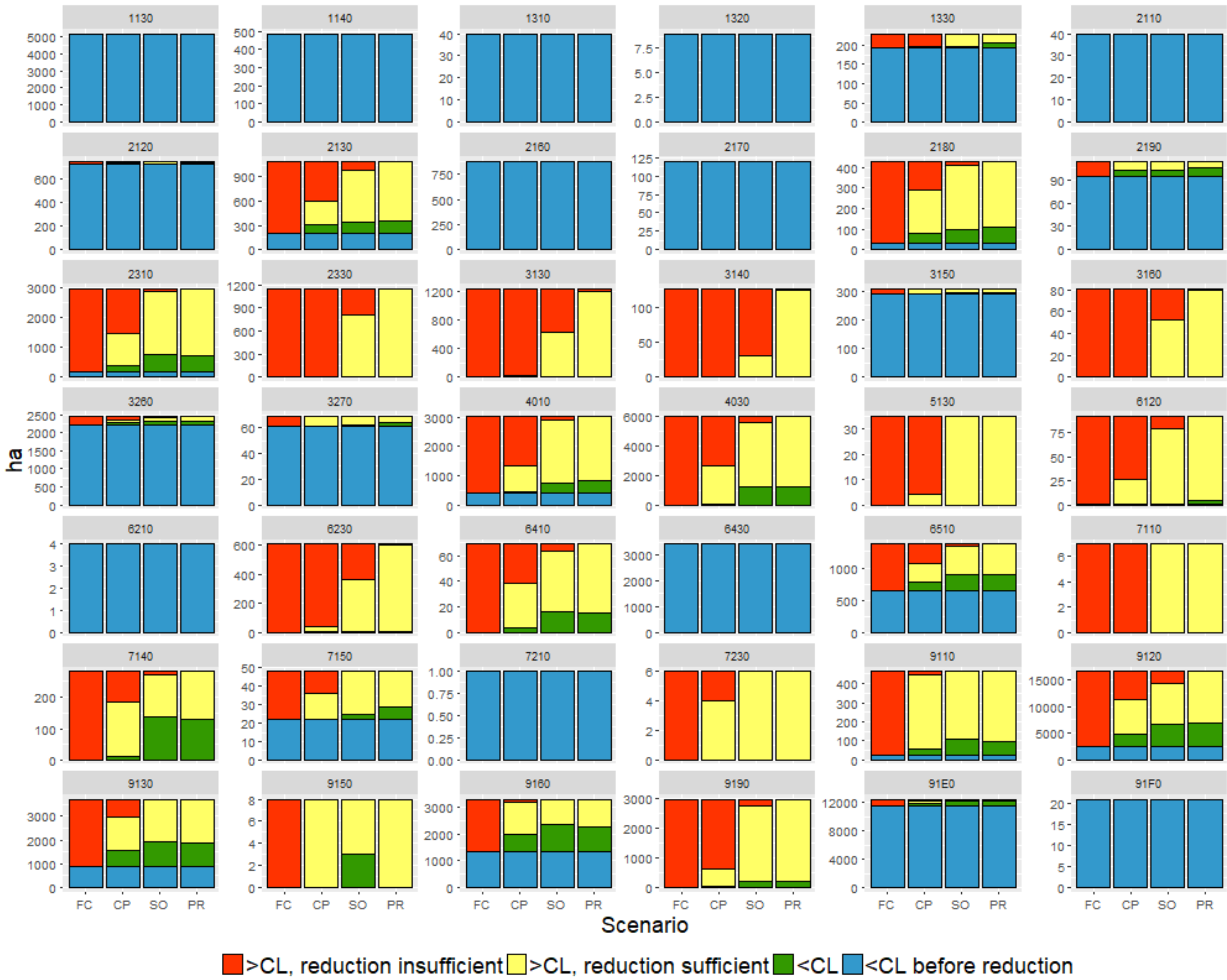
Supplementary material

Supplementary Table 1: Main model outputs.

Level	Total number	Main output variables	Unit
Emission source (animal housing)			
Stable	44540	Emission Number of Animals Abatement Cost Stable occupation	kg NH_3 yr^{-1} None (scalar) € %
Farm	23408	Emission Number of Animals Abatement Cost Profit Aggregate Deposition Score	kg NH_3 yr^{-1} None (scalar) € € None (scalar)
Animal Category	38	Total Number of Animals	None (scalar)
Farm Type	15	Emission Profit Aggregate Deposition Score Number of closed stables Number of closed exploitations	kg NH_3 yr^{-1} € None (scalar) None (scalar) None (scalar)
Sector	5	Emission Profit Aggregate Deposition Score	kg NH_3 yr^{-1} € None (scalar)
Stable Type	84	Number of Stables per Stable Type	None (scalar)
Additional Emission Abatement	6	Number of times additional emission abatement option is applied	None (scalar)
Receptor (protected habitats)			
Protected Habitat	71787	Total Deposition Deposition from local sources Habitat Class Abatement Cost	kg N ha^{-1} yr^{-1} kg N-NH_3 ha^{-1} yr^{-1} None (categorical) € ha^{-1} yr^{-1}
Habitat Type	42	Total hectares per habitat class Average Total Deposition Critical Load exceedance	None (scalar) kg N ha^{-1} yr^{-1} %
Habitat Class	4	Total hectares per habitat class	None (scalar)
Natura 2000 area	38	Total hectares per habitat class Average Total Deposition Critical Load exceedance	None (scalar) Kg N ha^{-1} yr^{-1} %
Administrative unit			
Municipality	308	Emission Profit Aggregate Deposition Score Abatement Cost	kg NH_3 yr^{-1} € None (scalar) €
Region	1	Emission Profit Aggregate Deposition Score Number of closed stables Number of closed exploitations Abatement Cost Average Total Deposition Critical Load exceedance	kg NH_3 yr^{-1} € None (scalar) None (scalar) None (scalar) € kg N ha^{-1} yr^{-1} %



Supplementary Figure 1: *Distribution of habitat classes for 42 habitat types occurring in Flanders. FC: Full Capacity. CP: Current Policy. SO: Spatial Optimization. PR: Proportionate Reduction. See Annex 1 of the Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora) for a list the habitat types* (Council of the European Union, 1992).

Supplementary Table 2: Emission abatement cost allocation per habitat. *The table shows the principle of cost allocation per habitat, with a fictional example of two farms (F1 and F2), and 3 habitats (H1, H2, H3). F1 has an impact on H1, H2 and H3. F2 has an impact on H1 and H2.*

Farm	**Abatement Cost Farm**	**Habitat**	**Deposition**	**Fraction of Deposition**	**Abatement Cost Habitat**
F1	AC_{F1}	H1	$Dep_{F1,H1}$	$F_{F1,H1} = Dep_{F1,H1} / (Dep_{F1,H1} + Dep_{F1,H2} + Dep_{F1,H3})$	$AC_{F1,H1} = F_{F1,H1} * AC_{F1}$
		H2	$Dep_{F1,H2}$	$F_{F1,H2} = Dep_{F1,H1} / (Dep_{F1,H1} + Dep_{F1,H2} + Dep_{F1,H3})$	$AC_{F1,H2} = F_{F1,H2} * AC_{F1}$
		H3	$Dep_{F1,H3}$	$F_{F1,H3} = Dep_{F1,H1} / (Dep_{F1,H1} + Dep_{F1,H2} + Dep_{F1,H3})$	$AC_{F1,H3} = F_{F1,H3} * AC_{F1}$
F2	AC_{F2}	H1	$Dep_{F2,H1}$	$F_{F2,H1} = Dep_{F2,H1} / (Dep_{F2,H1} + Dep_{F2,H2} + Dep_{F2,H3})$	$AC_{F2,H1} = F_{F2,H1} * AC_{F2}$
		H2	$Dep_{F2,H2}$	$F_{F2,H2} = Dep_{F2,H1} / (Dep_{F2,H1} + Dep_{F2,H2} + Dep_{F2,H3})$	$AC_{F2,H2} = F_{F2,H2} * AC_{F2}$

Abatement Cost H1	$AC_{H1} = AC_{F1,H1} + AC_{F2,H1}$
Abatement Cost H2	$AC_{H2} = AC_{F1,H2} + AC_{F2,H2}$
Abatement Cost H3	$AC_{H3} = AC_{F1,H3}$