

A screening procedure to measure the effect of uncertainty in air emission estimates

Alessandra La Notte¹  · Stefania Tonin¹ · Silvio Nocera²

Received: 27 February 2017 / Accepted: 26 February 2018 / Published online: 22 March 2018
© Springer Science+Business Media B.V., part of Springer Nature 2018

Abstract Emission inventories are compiled at regional level. When these sources of information are used, uncertainty of emission estimates is never considered. In this paper, we propose an initial screening to identify whether and to what extent uncertainty related to emission inventories affects quantitative analysis used to set strategies and implement actions at regional and subregional levels. We consider the regional air emission inventory of the Piedmont region in Italy. For each pollutant and each sector, uncertainty is calculated by adapting the insurance-based method. A hybrid accounting matrix is built, three environmental themes are analyzed, and a shift-share analysis is undertaken considering jointly air emission estimates and the number of employees at regional and provincial levels. The same procedure is undertaken for data processed with and without uncertainty. Based on the obtained outcomes, few comments are drawn in order to reach some general conclusion to feed discussion on the importance of integrating and prioritizing uncertainty into decision-making at subnational level.

Keywords Uncertainty · Air emission inventory · Hybrid environmental accounts · Global warming potential · Acidification · Shift-share analysis

While undertaking this research Alessandra La Notte was a research fellow at IUAV. Alessandra La Notte's current position is at the European Commission Joint Research Centre - Directorate D: Sustainable Resources.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11027-018-9798-8>) contains supplementary material, which is available to authorized users.

✉ Alessandra La Notte
alessandra.la-notte@ec.europa.eu; lanotte@iuav.it

¹ Department of Design and Planning in Complex Environments, IUAV University of Venice, Santa Croce 191, Tolentini, 30135 Venezia, Italy

² Department of Architecture and Arts, Università Iuav di Venezia, Dorsoduro 2196, 30123 Venezia, Italy

1 Introduction

Air emission inventories, particularly greenhouse gas (GHG) emissions, have always been thought of as the primary source of information for international climate change agreements and trading (IPCC 2006; Lieberman et al. 2007). These have been compiled mainly at a national level, but when developed at the subnational level, these datasets can be a precious source of information for policymakers at different administrative levels, in accounting terms, for descriptive analysis and for policy analysis. However, although regional air emission inventories are routinely used, for example, by regional environmental protection agencies to assess the state of the environment, uncertainty is never considered. In some cases, uncertainty coefficients are not even available from the agencies and institutes responsible for the delivery of air emission inventories. However, accounting for uncertainty can often remarkably change an environmental and also, thus, political assessment based on emission inventories.

With respect to the random component of uncertainty obtained from expert judgment, uncertainty analysis deals with random errors based on the inherent variability of a system and the finite sample size of the available data (IPCC 2006). In previous work (Tonin et al. 2016), we addressed the issue of uncertainty in GHG inventories by considering its causes and how to improve the measurements (i.e., data production, data analysis, and data use). We ended up plotting a use-chain model where, when moving from the field of the biophysical environment to the field of social sciences and to decision-making, the analysis of uncertainty expands from (i) quantitative, mainly statistical methodologies aimed at improving the detail of the data to (ii) flexible open approaches aimed at integrating quantitative and qualitative information.

The content of the use-chain model is based on recent literature about uncertainty analysis; an important role in this review is played by the International Workshops on Uncertainty in Greenhouse Gas Inventories, which specifically target the sources of data we make use of. Some previous analyses (Lieberman et al. 2007; White et al. 2011) have highlighted the fact that initially, most workshop contributions, more generally, were more oriented toward data production and referred to the uncertainty related to measurement and to the lack of data. Regarding policy analysis, the experts considered the role of uncertainty in those policy tools that directly depend on emission inventories, such as climate change compliance rules and emission trading schemes. From the most recent workshop, it is worthwhile to note that in terms of data analysis, particularly of integration with other datasets, an increased number of presentations related to the employment of spatial GHG inventories for what concerns economic sectors. Important examples include Charkovska et al. (2018) for the agricultural issue, Halushchak et al. (2015) for fossil fuel extraction, Topylko et al. (2015) for electricity generation, and Charkovska et al. (2015) for industrial activity.

Reducing uncertainty involves a cost in terms of time, human resources, and additional information, so it would be useful to know whether and where the use of such effort is worthwhile (Nocera et al. 2015). Whether it is worthwhile can depend on many different identified criteria, and these need to be clearly presented and justified. The purpose of this paper is to contribute by proposing an initial screening whose aim is to identify situations where the additional work of assessing uncertainty is indeed needed; the paper also suggests basic criteria to justify the choice.

The case study used in this paper moves beyond the traditional contexts (i.e., compliance rules and emission trading) and scale (i.e., national) and shows the possible effects of

uncertainty at a subnational level by using tools that are available for local policy action. To screen for uncertainty, we designed a composite approach; an insurance-based method is combined with a hybrid environmental accounting framework to facilitate both descriptive and policy analyses. The descriptive analysis is based on a set of environmental indicators, while the policy analysis is based on a decomposition analytic tool.

Thanks to this initial screening, it is possible to assess rough estimates with and without uncertainty and check their effect on the information provided to policymakers. This will be the basis of understanding whether and to what extent some work on uncertainty (that moves beyond the initial screening) must be undertaken, because estimates including uncertainties will change policy strategy and actions.

The Piedmont region in Italy and its provinces were selected as the case study in which the methodology, the accounting framework, the environmental indicators, and the decomposition analysis will be applied. We chose this case study because the air emission regional inventory is one of the best examples of such inventories in Italy. Their datasets are publicly available, and the uncertainty coefficients have been efficiently compiled by the functionaries in charge of the inventory.

2 Materials and methods

After describing the Piedmont region and its provinces, this section presents the basic accounting module, National Accounting Matrix including Environmental Accounts (NAMEA), used for this analysis. The initial description of the module does not include uncertainty, but in the following subsection, uncertainty is addressed by employing an insurance-based method. Finally, two analytic tools are described: the set of indicators that constitute the environmental themes and the shift-share analysis.

2.1 The Piedmont region and its provinces

The Piedmont region is located in the northwestern part of Italy. In Piedmont, the automotive sector (the FIAT group and activities that surround it) is the dominant industry, followed by the chemical, food, textile, clothing, electronics, and editorial industries. It is important to identify the main locations of all these sectors throughout the region in order to establish a connection with emitted pollutants, starting from the province where Turin, the capital city of the region, lies.

Turin has always been known as the city of cars and has always had a strong connection to that type of industrial production, mainly based on iron compartments. Another important industry in the province is located in the Ivrea area, where a big Italian company (Olivetti) has developed manufacturing focused on electronics and informatics. The cluster of nanotechnology being developed in the province of Turin is a multifaceted enterprise system, from information and communication technologies to biotechnology, aerospace, and audiovisual as well as publishing, banking, and industrial design systems.

Most of the other provinces have industrial profiles, especially Alessandria, Biella, and Verbano-Cusio-Ossola (VCO). In Novara and Cuneo, a variety of activities include agriculture, which also plays an important role in Vercelli and plays an almost exclusive role in Asti.

Several industrial sectors have been developed in the Alessandria province, including many specializing in the molding of plastics and chemicals, in heavy engineering, in the confectionery industry, in the production of Borsalino felt hats, and in the processing of precious metals, especially gold. The territory is also an important logistics hub, due to its proximity to the port of Genoa and thanks to its strategic location, which allows transport to the major cities of northern Italy. This allows for the better management of goods arriving and departing from the port, and thus, this is where transport and storage activities are located. With respect to the agricultural sector, there are large cereal plantations, in particular wheat and corn as well as paddy fields.

The Biella province is one of the world centers of textiles and wool and of a general textile machinery sector. The district specializes in the production of fabrics for men and women, of yarns for weaving and knitting, and in all auxiliary processes of the wool textile industry (combing, dyeing, finishing, etc.).

The area of Verbano-Cusio-Ossola boasts a long industrial tradition, both in field extraction (marble and red granite quarries) and manufacturing plants, which settled in that territory due to the good availability of hydropower. There is considerable production of cookware, tableware, and small appliances. In recent years, the energy sector has been characterized by strong production and employment growth, and it recorded an increase in total renewable energy production (e.g., hydroelectric energy, photovoltaic energy).

Because of its position between two of the most important Italian regions, the province of Novara is an important crossroads for commercial traffic along the roads connecting Milan to Turin and Genoa to Switzerland. The Centro Intermodale Meris is the most important center of railway marshalling in northeastern Piedmont, a crucial point for trains incoming from and departing to northern Europe (especially Belgium and the Netherlands). Rice cultivation is a massive presence in the southern part of the province. With the provinces of Vercelli and Lomellina (Lombardy), Novara forms the famous “Triangolo dei chicchi d’oro” (gold grain triangle), which produces about 50% of the total Italian rice yield. The second most widespread crop is corn, while the floriculture sector is also relevant. In the plains, breeding is mainly practiced and cows’ milk is used to produce typical gastronomic products. There are several industrial districts in this area, with companies representing Italian excellence not only in chemistry and metallurgy but also in precision engineering and industrial machinery, textiles, publishing and paper, and food industries.

In Cuneo, the agricultural sector plays an important role (nearly 30% of total business). However, a variety of manufacturing activities are active in the territory, from the textile industry to the confectionery industry and baked goods, to the publishing industry as well as a significant share of companies in machinery and material production.

In Vercelli, the tertiary sector employs the most workers. Agriculture retains significant relevance, in particular for rice production. In the secondary sector, the mechanical industry is characterized by high production specialization in taps and valves. The textile industry also has a strong industrial tradition and exports products most significantly. Some of the major business realities include the leading biomedical and biotech cluster in Piedmont, while chemicals are another major growth area.

Most of the territories of the province of Asti are classified as intermediate rural areas, often hilly, with permanent agriculture and specializing primarily in grape and, thus, in wine production. In this province, we mainly find agro-food systems that, thanks to remarkable brands of wine and food products, favor exports and a notable increase in tourism.

2.2 The hybrid environmental accounts and the insurance-based approach

This section describes the tools employed for the application. First, the NAMEA module allows the connection of economic accounts with environmental data (in our case, air emissions); since emission data present uncertainty, we then introduce an insurance-based method to check how far the estimate can change when uncertainty is taken into account.

2.2.1 Hybrid accounts applied at the local level

The NAMEA (Keuning 1993; de Haan and Keuning 1996; de Boo et al. 1993) is a statistical information system that combines national and environmental accounts in a single matrix; it is based on the input-output approach of Leontief (1970). In NAMEA, the economy is divided into sectors whose contributions to economic and environmental indicators are tracked. This is called a hybrid accounting system because economic aspects are represented in monetary units and environmental aspects in physical units. The fundamental idea of NAMEA is to supplement the conventional national accounting matrix with additional environmental accounts that record the emissions of pollutants. It is also possible to account for environmental themes, such as the greenhouse effect, ozone layer depletion, and acidification.

NAMEA is usually applied at a national level. However, a project (referred to as RAMEA or the Regional Accounting Matrix including Environmental Accounts) was launched to experiment with the application of such hybrid accounts at the regional level. In the RAMEA project, the regional NAMEA-type matrices were prepared for four European regions: Emilia-Romagna (ARPA Emilia-Romagna, lead partner), Noord-Brabant (TELOS, Brabant Centre for Sustainable Development), Małopolska (Mineral and Energy Economy Research Institute of the Polish Academy of Sciences), and South-East England (SEEDA, Environment Agency, Cambridge Econometrics).

Other than RAMEA, some additional experiments of NAMEA-type applications were further tested in Piedmont at regional, provincial, and municipal levels for air emissions and waste (La Notte and Dalmazzone 2012; Dalmazzone and La Notte 2013).

In this paper, we focus on regional and provincial accounts for air emissions in Piedmont. The environmental accounts of the Piedmont NAMEA-type table are compiled with the support of regional emission inventories provided by the Piedmont regional authorities, which follow the EMEP-CorinAIR¹ inventory. This inventory was compiled since the beginning of the 2000s (specifically for the years 2001, 2005, 2008, and 2010). The estimate procedure has been greatly improved and updated over the years, generating many releases. The regional inventory records data according to the Selected Nomenclature for Air Pollution (SNAP) classification, comprising 11 macro sectors, 75 sectors, and 430 activities for the following pollutants: methane (CH₄), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen dioxide (N₂O), ammonia (NH₃), volatile organic compounds (VOC), oxides of nitrogen (NO_x), sulfur dioxide (SO₂), and particulate matters (PM₁₀ and PM_{2.5}).

The NAMEA-type accounting module allows one to frame together economic data and emissions, and it can be compiled at a local level. The first step is to harmonize the SNAP

¹ The CORE Inventory AIR emissions (CORINAIR) method is the framework supported by the European Environment Agency. It was adopted by all protection agencies in compiling the national inventory. (EMEP refers to the European Monitoring and Evaluation Programme.)

classification system, which is based on production processes, with the *Nomenclature générale des Activités économiques dans les Communautés Européennes* (NACE) classification system, which is based on economic sectors. Economic data (local units and number of employees) are drawn from *Archivio Statistico delle Imprese Attive* (ASIA, statistical inventory of active firms), while air emission data are taken from EMEP-CorinAIR (in tons for all pollutants except CO₂, which is in 1000 t). ASIA is the register of active enterprises that integrates national administrative archives with other sectorial registers and with the Italian national STATistical institute (ISTAT) surveys. The aim of ASIA is to provide statistical information every year on the territorial distribution of economic activities and on employment. An ad hoc methodology, in fact, converts the administrative data into statistical information to estimate and validate the characteristics of the identified statistical units.

It is possible to connect air emissions to their generating activity by taking the EMEP 75 sector emissions and allocating them to the corresponding NACE subclasses; that is, SNAP sector-by-sector emissions can be aggregated within the six NACE code classes (the most detailed subclassification available) in order to guarantee as much as possible that all the available information is used in a consistent way. The hybrid account NAMEA, which does not include uncertainty, is discussed in Section 3 of this paper.

2.2.2 The insurance-based approach applied to hybrid local accounts

Approaches proposed to reduce uncertainty can be of different types and be used for different purposes (Tonin et al. 2016). For this application, a methodology based on the mechanism of insurance companies has been chosen. Marland et al. (2014) borrow an approach specifically from life insurance policies, as applied by insurance industries. The approach consists of the addition of a risk charge into their fees to cover the net present value of expected payouts; this represents a sort of insurance for the insurer. The risk charge can be obtained by multiplying the percentage of uncertainty for the price per ton of carbon, so that finally, the price of the released carbon and the risk charge can be added up. The risk charge per ton of carbon (or carbon equivalent) can be determined through this procedure and can be added to the central estimate to complete the estimation of the emissions. This approach follows in the footsteps of the adjustment of emissions to attain some level of confidence in reporting the emissions (Gillenwater et al. 2007; Jonas et al. 2010).

With an initial rough procedure, this logic can be applied in order to screen which pollutants require a deeper analysis; once critical pollutants and critical territorial contexts are pinpointed, more sophisticated approaches can be applied to provide the policymaker with a more robust assessment. However, we must be aware that with this approach, (i) we only address the issue of imprecise estimates and do not consider the issue of inaccuracy and (ii) we do not apply the risk charge concept to accounting emissions at some point in the future.

The risk charge formula applied for the initial screening is taken from the EMEP-CORINAIR methodology (EEA 2013, 2016). This formula is used here to calculate an initial rough estimate of emissions that include uncertainty:

$$EUnc_{ijk} = (E_{ijk} \times (1 - UNC_{ijk})) + E_{ijk}, \quad (1)$$

where E_{ijk} is the emission for activity i , pollutant j , and fuel k ; UNC_{ijk} is the uncertainty coefficient for activity i , pollutant j , and fuel k ; and $EUnc_{ijk}$ is the emission estimate

considering uncertainty for activity i , pollutant j , and fuel k . When the uncertainty coefficients are reported as 0%, the estimated value is doubled; when they are reported as 100%, they remain the same. This approach can provide interesting insights to assess the robustness of the inventory datasets. This formula was received from the emission inventory functionaries and was further discussed with them in order to ensure a consistent and coherent application. Of course, more sophisticated formulas could be applied; however, since this application is used for an initial screening, we accepted and applied what is currently used as common practice.

The total uncertainty coefficient for activity i , pollutant j , and fuel k can be calculated through the information available from the emission inventory, which provides uncertainty coefficients for emission factors (EF) and for activity data (AD) at the most refined level (430 activities). It is thus possible to process initial estimates by adding the uncertainty for each activity in terms of the emissions factor and the activity data and then combining them (EEA 2013, 2016). Here we follow uncertainty only proportionally by means of:

$$UNC_{ijk} = UnEF_{ijk} \times UnAD_{ijk}, \quad (2)$$

where $UnEF_{ijk}$ is the uncertainty coefficient assigned to EF for activity i , pollutant j , and fuel k ; $UnAD_{ijk}$ is the uncertainty coefficient assigned to AD for activity i , pollutant j , and fuel k ; and UNC_{ijk} is the total uncertainty coefficient for activity i , pollutant j , and fuel k . Emission inventories are usually injected into any assessment (from monitoring to policy analysis) as known systems. The use of Eq. (2) breaks this assumption; the emission estimates are not taken as an a priori accepted system. Here we follow the footsteps of other authors. For instance, Jonas and Nilsson (2007) have also questioned the underlying systems perspective by applying uncertainty classes to emission inventories.

In this specific application, the coefficients have been used as follows: the minimum level is the emission estimate as reported in the official inventory, and the maximum level is the outcome of Eqs. (1) and (2) with no range of uncertainty applied (e.g., through the application of the Monte Carlo method, as suggested in the IPCC guidelines). As such, the approach undertaken shows the worst situation that could ever take place; all the inventory data (except those with an uncertainty coefficient equal to 1) underestimate the emissions at the highest value of their uncertainty coefficient. From the worst scenario, the most striking situations can emerge and catch the attention.

The uncertainty coefficients for emission factors and activity data depend on how estimates are measured and processed. Details concerning the meaning of the uncertainty coefficients $UnEF$ and $UnAD$ in the Piedmont inventory are explained in Table 1.

The adopted procedure considers the calculation of uncertainty-modified estimates of the 10 emissions for EF and for AD, for each of the 430 inventory activities. We then aggregate the 8600 records into sectors and households, ensuring that there is consistency with the NACE classification system. The NAMEA-type table is built by entering ASIA data on the economic side and inventory emission data on the environmental side, according to the NACE classification.

2.3 The environmental themes

In order to assess the potential aggregated impact of a number of different air emissions within the same environmental theme, it is possible to combine several air emissions into

Table 1 Uncertainty coefficients assigned to emission factors and activity data

Classes	Description	Uncertainty coefficient
Emission factors		
A	Estimate based on a large number of measures in a large number of installations which represent the whole sector	1
B	Estimate based on a large number of measures in a fair number of installations which represent part of the sector	0.8
C	Estimate based on some measures in a small number of representative installations or on engineering judgment based on a significant number of facts	0.6
D	Estimate based on a single measurement or on engineering judgment based on a significant number of facts and few assumptions	0.4
E	Estimate based on an engineering calculation based solely on assumptions	0.2
L	Value assumed equal to half of the detection limit	0.1
P	Value obtained by scaling the 2004 data in AIA	0.2
T	Valued declared in the Emission Trading	0.8
U	Valued declared in EPRTR	0.8
V	Data processed by AIA	0.8
W	Data processed by Provincia di Torino	0.8
Y	Data processed through data of IEA	0.8
Z	Air emissions from ex DPR 203	0.8
Activity data		
0	Missing data	0
A	Data accurately measured at municipal level for the whole sector and throughout the region	1
B	Data collected at municipal or provincial level for part of the sector and extended to the whole sector on the basis of other statistical indicators	0.8
C	Data derived from publications and available aggregated at the regional level	0.6
D	Data from sector studies by organizations or institutions at national level	0.4
E	Extrapolation based on other data or indicators at national level	0.2
P	Value obtained by scaling the 2004 data in AIA	0.2
T	Valued declared in the Emission Trading	0.8
U	Valued declared in EPRTR	0.8
V	Data processed by AIA	0.8
W	Data processed by Provincia di Torino	0.8
Y	Data processed through data of IEA	0.8
Z	Air emissions from ex DPR 203	0.8

Source: Adapted from the Regional Air Emission Inventory for the Piedmont region 2010

one indicator by introducing conversion factors. We will consider three environmental themes, each corresponding to a selected indicator (Eurostat 2015).

The first theme concerns the greenhouse effect, the atmospheric-climatic phenomenon caused by emitting CO₂, CH₄, and N₂O, which contribute to global warming. These gases have specific thermal potentials that we can quantify as coefficients to convert them into CO₂ equivalents. We use the global warming potentials (GWPs) of gases to calculate the total emissions in a CO₂ equivalent—1 for CO₂, 21 for CH₄, and 310 for N₂O (ISTAT 2009; Eurostat 2015). The time period usually used for GWPs is 100 years.

The second theme concerns the phenomenon of acid rain, or the fallout from the atmosphere of acid particles, acid molecules diffused into the atmosphere that are captured and deposited on the ground by precipitation. The issue of acidification (ACID) is mainly caused by gas emissions such as NO_x, oxides of sulfur (SO_x), and NH₃. In order to

aggregate the emissions of these pollutants, we multiply each gas for its potential acid equivalent (PAE), which is 1/46 for NO_x , 1/32 for SO_2 , and 1/17 for NH_3 (ISTAT 2009²).

The third theme concerns high tropospheric ozone concentrations that are harmful to human health and ecosystems. The main atmospheric emissions that contribute to the phenomenon are CH_4 , NO_x , VOCs, and CO. These emissions have their own coefficients to determine the tropospheric ozone formation potential (TOFP). The coefficients to be used are 0.014 for CH_4 , 1.22 for NO_x , 1 for VOCs, and 0.11 for CO (ISTAT 2009; Eurostat 2015). The results are discussed in Section 3.1.

2.4 The shift-share analysis

The shift-share analysis is a tool commonly used in regional science to determine whether a regional economy has competitive advantages over the larger (national) economy. The process considers the change over time of an economic variable (e.g., value added, employment) within economic sectors and then divides that change into various components. In our case study, we consider the regional level as the larger economy and the provincial level as the target, to identify competitive advantages. The shift-share analysis, combined with the hybrid accounts at the regional and provincial levels, allows an explanation of the reasons for different economic performances throughout the territory as well as an identification of a good production mix between specific emissions and economic/social efficiency by decoupling economic development from the increase in emissions. We can in fact apply decomposition analysis in order to investigate the mechanism that affects air emissions, splitting an entity into its components. Changes in some variables are decomposed in variations in its determinants. The methodologies commonly used to decompose emissions trends are index decomposition analyses, input-output structural decomposition analysis, and shift-share analysis. The latter has already been applied to compare regional and national data (Esteban 2000; Mazzanti et al. 2007) and regional–provincial and provincial–municipal data (La Notte and Dalmazzone 2012).

The purpose of this application is to measure the role of the productive structure at the lower hierarchical level considered (in our case, the provincial level) in explaining the emissions efficiency gap between this level and the higher hierarchical level (in our case, the regional level). Shift-share analysis, in fact, decomposes the source of change of the specified “dependent variable” into provincial-specific components (which constitutes the shift) and the portion that follows regional growth trends (which constitutes the share).

We aim to address the question of whether the gap between the considered province and the regional benchmark average depends on environmental-friendly technologies (or the lack of them) in the included economic sectors and/or on a provincial specialization in sectors with higher/lower eco-efficiency.

We first calculate the intensity of the emissions by considering each pollutant with reference to the number of workers employed in each sector. This variable provides insights into the socioenvironmental efficiency of the productive sectors, which is useful in planning a strategy to support environmental innovation at the sector level. We then analyze the relative environmental efficiency of the provincial economic system with

² The formula reported by Eurostat (2015) considers SO_x with a different coefficient. Because the emission inventory records SO_2 , we decided to use the ISTAT coefficient.

respect to the regional average, referring to the GHG pollutants and to the economic sectors included in the hybrid accounts.

The aggregate indicator of emission intensity is represented by “total emissions [E] on number of employees [Empl].” The benchmark is represented by the regional value. This indicator is decomposed as the product of $(E^s/Empl^s) \times (Empl^s/Empl)$, where $(Empl^s/Empl)$ is the share of sector $Empl$ on the total $Empl$ for all sectors s , with the value of s defined from 1 to h (where h is the number of NACE sectors included in the regional NAMEA).

We define the index of emission intensity as X for the regional average ($X = E/Empl$); as X_{Pr} for the province, $X_{Pr} = \frac{E_{Pr}}{Empl_{Pr}}$; and as X_s for each sector for both the province, $X_{Pr}^s = E_{Pr}^s/Empl_{Pr}^s$, and for the region, $X^s = E^s/Empl^s$. We then define the share of total employment as $P^s = Empl^s/Empl$ for the region and as $P_{Pr}^s = Empl_{Pr}^s/Empl_{Pr}$ for the province

$$X = \sum_s P^s X^s \tag{3}$$

$$X_{Pr} = \sum_s P_{Pr}^s X_{Pr}^s \tag{4}$$

The shift-share decomposition allows the identification of three effects that explain the gaps, in terms of the aggregate emissions efficiency, between the province and the region.

The first effect (“structural” or industry mix) is given by:

$$m_{Pr} = \sum_s (P_{Pr}^s - P^s) X^s, \tag{5}$$

where m_{Pr} assumes a positive or negative value, respectively, if the region is “specialized” in sectors associated with lower or higher environmental efficiency, given that the gap in total shares is multiplied by the value of X of the regional average (“as if” the province were characterized by the average regional efficiency). The factor m_{Pr} assumes lower values if the province is specialized in (on average) more efficient sectors.

The second factor (“differential” or “efficiency”) is given by:

$$p_{Pr} = \sum_s (X_{Pr}^s - X^s), \tag{6}$$

where p_{Pr} assumes a positive or negative value, respectively, if the region is less or more efficient in terms of emissions (the shift between provincial and regional efficiency), under the (“as if”) assumption that the share of the number of sector employees were the same for the region and the province.

The third effect (“allocative component”) is given by:

$$a_{Pr} = \sum_s (X_{Pr}^s - X^s) (P_{Pr}^s - P^s). \tag{7}$$

The a_{Pr} factor is positive or negative, respectively, if the province is specialized, relative to the regional benchmark, in sectors characterized by a higher or lower emission intensity.

The outcomes of the shift-share analysis are shown for each province as [Supplementary Material](#) and are discussed in Section 3.2.

3 Results

3.1 The accounting module

Table 2 presents the hybrid accounts for the Piedmont region. All economic sectors except the primary sector (i.e., agriculture, forestry, and fishing) are included. In order to compile the economic module for the account and avoid resorting to the economic territory and residence principle,³ we use the ASIA database, which does not include the primary sector. By using this database, we ensure consistency with emission inventory data, but we cannot include either the economic or the environmental side with respect to the primary sector. When the uncertainty maximum limit reported in Table 1 is applied to the estimates of Table 2, we obtain Table 3.

Hybrid accounting tables with and without uncertainty have been compiled for each individual Piedmont province to enable both the assessment of environmental themes and the shift-share analysis.

3.2 The environmental themes

In our application, we first calculate the three environmental themes for the hybrid accounting table without uncertainty; we then calculate the same indicators for the hybrid accounting table with uncertainty (Table 4). Two elements deserve attention: (i) the total amount of pollutants that affect the environmental theme and make one province more environmentally vulnerable than others and (ii) the role played by uncertainty in modifying the estimates. The former is relevant for policymakers, because in environmentally vulnerable provinces, it is important to have reliable and accurate estimates; the latter is relevant because uncertainty plays a major role in processing the final estimates. Each of the two cases justifies a detailed uncertainty assessment.

The immediate way to interpret the results of the environmental themes is to consider the difference between the indicators calculated without uncertainty (w/o Unc) and those calculated with uncertainty (w Unc) in order to check the robustness of the inventory data. The role played by uncertainty can, in fact, affect the strategic analysis in setting environmental priorities.

Torino has the highest value related to GWP; this remains the highest value even when uncertainty is taken into account. However, Fig. 1 clearly shows how uncertainty increases the estimates in all provinces, with peaks in Biella and Novara. This can be explained by the fact that pollutants such as CO₂ and CH₄ have a high uncertainty in SNAP 03 and SNAP 04, corresponding to the NACE manufacturing activities (in particular in the textile sector) based in Biella, as well as in SNAP 07, which concerns Novara as a crossroads for commercial traffic. Inventory data for Torino, Biella, and Novara are not robust enough to ensure that a correct environmental perspective on GWP is adopted. This screening phase provides a signal that uncertainty should be considered and further processed.

Figure 2 shows the different estimates obtained for acidification when uncertainty is added. Once again, the province of Torino registers the highest estimates, both with and without

³ An economic territory consists of all the institutional units that are resident in that territory. The residence principle assigns each economic unit to the territory with which the unit has the strongest link, i.e., its predominant center of economic interest. Adopting a residence principle for corporations, for example, means considering the corporation a resident of the territory in which it was created.

Table 2 Hybrid accounts for the Piedmont region (2010)

	<i>Economic activities (secondary and tertiary sectors NACE 06-96)</i>	<i>Employees (number of workers)</i>	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
06	<i>Extraction of crude petroleum and natural gas</i>	615.86	0	0	0	0	0	0	0	0	0	0
07	<i>Mining of metal ores</i>	1.41	0	0	0	0	0	0	0	0	0	0
08	<i>Other mining and quarrying</i>	1380.86	0.000755	0.021967	5.7544	0.005539	0.000881	0	0.081825	0	0	0.008875
09	<i>Mining support service activities</i>	6.00	0	0	0	0	0	0	0	0	0	0
10	<i>Manufacture of food products</i>	33,636.06	15.64964	170.1602	460.11519	4919.568	8.316681	2.131408	784.3950	37.80410	27.41227	221.1067
11	<i>Manufacture of beverages</i>	4607.93	1.984721	19.89194	57.93831	316.3964	0.670199	0.130021	66.51890	8.338742	4.694170	15.35273
12	<i>Manufacture of tobacco products</i>	22.08	0.004358	0.036759	0.197391	0.034887	0.002731	0	0.236675	0.001844	0.001716	0.019998
13	<i>Manufacture of textiles</i>	22,592.18	5.525900	51.51774	210.9803	50.70990	3.857065	0.703893	293.9149	7.000331	6.384581	155.9827
14	<i>Manufacture of wearing apparel</i>	10,044.57	4.669157	34.49923	144.9806	67.96472	3.840279	0.924580	228.1213	6.124194	5.525796	147.4425
15	<i>Manufacture of leather and related products</i>	1207.73	0.618248	4.569089	19.51169	9.960623	0.560245	0.137393	32.13743	0.932178	0.851931	21.96069
16	<i>Manufacture of wood except furniture</i>	10,907.84	4.262546	56.60090	132.3988	1315.317	2.076849	0.540714	243.9558	14.97146	13.67088	53.54723
17	<i>Manufacture of paper and paper products</i>	6148.86	2.370522	65.66807	538.5802	813.1742	1.649945	0.718268	283.9702	27.00883	22.95342	55.88562
18	<i>Printing and reproduction of recorded media</i>	8698.14	3.108553	52.72591	103.0752	408.9344	1.931840	0.795746	156.5515	4.58902	3.450035	53.62021
19	<i>Manufacture of coke and refined petroleum products</i>	1340.20	2.479258	72.43435	417.8689	643.2059	3.569351	0.554810	870.1859	35.86978	11.81079	1786.813
20	<i>Manufacture of chemicals and chemical products</i>	10,539.51	615.775	92.57034	255.7775	3044.844	1823.491	1.400975	683.8469	29.18082	24.06563	1311.515
21	<i>Manufacture of pharmaceutical products</i>	2425.55	1.717815	10.41030	57.68597	90.88101	1.903531	0.660965	135.6103	4.558933	4.295595	79.93187
22	<i>Manufacture of rubber and plastic products</i>	24,704.26	8.666940	124.2190	273.7312	1102.659	3.771159	1.812308	379.8516	128.0726	55.19512	81.03381
23	<i>Manufacture of other nonmetallic mineral products</i>	13,388.79	16.07556	507.4165	1345.866	323.7679	12.4283	33.64632	3866.178	137.2450	81.89992	1028.191
24	<i>Manufacture of basic metals</i>	11,297.82	22.12995	1261.360	384.8613	969.7133	11.00912	21.98836	961.7815	91.89080	59.91276	570.6608
25	<i>Manufacture of fabricated metal products</i>	56,254.28	14.98729	191.3162	544.0188	389.3733	7.585492	2.433934	742.4259	14.33035	13.47805	121.5187
26	<i>Manufacture of computer, electronic and optical prds.</i>	8459.58	2.215076	18.36448	87.77298	128.4797	1.560895	0.751434	120.9693	3.843910	3.291325	39.34502
27	<i>Manufacture of electrical equipment</i>	14,156.83	12.26891	69.30359	401.5854	265.5121	13.82867	1.143376	662.0612	18.03644	16.11996	571.1620
28	<i>Manufacture of machinery and equipment</i>	54,011.62	14.49376	171.5394	486.6704	1044.488	6.743475	6.304507	706.1627	15.79524	14.81795	134.5206
29	<i>Manufacture of motor vehicles</i>	54,824.90	12.99598	178.9657	571.1391	2565.909	7.089453	5.560814	870.0720	12.53331	10.95310	85.30235

Table 2 (continued)

Economic activities (secondary and tertiary sectors NACE 06-96)		Employees (number of workers)	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
30	Manufacture of other transport equipment	11,290.78	3,207,671	38,679,89	127,6802	316,6385	1,832,185	1,214,219	194,0278	2,801,488	2,573,045	32,877,83
31	Manufacture of furniture	3728.48	1,552,744	13,68087	49,33397	1047,889	0,981,355	0,156,476	68,40646	1,823,386	1,674,849	30,724,83
32	Other manufacturing	13,496.68	5,426,001	63,95993	188,0525	182,7964	2,769,889	0,184,474	246,2645	8,690,590	8,412,136	71,794,82
33	Repair and installation of machinery and equipment	14,346.34	3,947,676	39,83820	138,1285	128,2053	1,721,291	0,460,051	172,7103	6,009,719	5,290,073	24,109,36
35	Electricity, gas, steam and air conditioning supply	7552.80	39,022,84	2038,229	6322,154	1689,760	80,26545	1,166,288	4677,654	58,02248	56,94594	301,5921
36	Water collection, treatment and supply	2282,67	0,826,711	7,891,610	27,90978	17,921,57	0,504,236	0,085,67	38,44456	1,017,227	0,950,998	14,684,22
37	Sewerage	898,31	1034,527	12,45085	99,59142	6,468,662	73,06338	1068,530	178,6894	5,219,571	4,610,503	192,9191
38	Waste collection, treatment and disposal activities	10,322,19	61,821,74	262,7808	355,6517	268,0374	168,8601	49,83323	1633,617	46,78740	46,48416	205,4621
39	Remediation activities, other waste management services	192,29	0,082,587	0,588,310	2,794,948	1,664,407	0,390,127	0,017,402	5,844,540	0,467,819	0,457,672	3,315,665
41	Construction of buildings	35,439,28	13,372,22	118,6579	440,4247	247,3718	8,552,152	1,518,694	615,2759	15,090,77	13,892,33	256,9251
42	Civil engineering	7043,53	3,046,615	30,83329	100,5952	68,98455	1,673,188	0,277,024	140,1426	3,711,299	3,482,327	48,06212
43	Specialized construction activities	97,505,12	33,78990	306,4951	1139,609	2179,564	20,48469	3,336,511	1545,493	36,48655	33,68066	570,9274
45	Wholesale and retail trade and repair of motor vehicles and motorcycles	34,233,57	1,587,427	15,87429	34,92344	208,6355	0,634,975	0	22,10971	0,127,010	0,127,010	0,317,486
46	Wholesale trade, except of motor vehicles and motorcycles	82,094,74	3,806,157	38,06151	83,73533	7,612,300	1,522,465	0	53,01208	0,304,529	0,304,529	0,761,225
47	Retail trade, except of motor vehicles and motorcycles	145,694,40	6,845,690	68,45690	150,6051	1936,066	2,738,275	0	95,34677	0,547,724	0,547,724	1,369,138
49	Land transport and transport via pipelines	44,416,29	288,5634	10,854,61	3864,896	2369,762	120,8760	31,98498	29,672,01	4688,288	1456,954	32,287,48
50	Water transport	92,50	0,003,341	0,053,416	0,117516	0,010,683	0,002,136	0	0,074398	0,000427	0,000427	0,001068
51	Air transport	393,08	0,153,244	367,3531	53,40225	149,8461	0,496,383	0,00221	197,2791	4,171,272	3,971,703	16,82681
52	Warehousing and support activities for transportation	24,080,48	1,162,586	11,62589	25,57696	2,325,182	0,465,034	0	16,19254	0,093,018	0,093,018	0,232,516
53	Postal and courier activities	13,110,32	0,614,413	6,144,143	13,51712	1,228,826	0,245,761	0	8,557,563	0,049,163	0,049,163	0,122,881
55	Accommodation	9499,23	0,461,415	4,614,159	10,15114	0,922,829	0,18457	0	6,426,599	0,036,922	0,036,922	0,092,285
56	Food and beverage service activities	70,899,98	3,331,194	33,311,98	73,28634	6,662,396	1,332,476	0	46,39691	0,266,528	0,266,528	0,666,241

Table 2 (continued)

	<i>Employees (number of workers)</i>	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
58	<i>Publishing activities</i>	4141.43	0.183716	1.837149	4.041721	50.28302	0.073486	0.301708	4.59344	0.018911	0.036743
59	<i>Motion picture and television program production</i>	1646.84	0.074495	0.744957	1.638905	0.148991	0.029794	0	1.037576	0.005955	0.014897
60	<i>Programming and broadcasting activities</i>	1692.28	0.073855	0.738565	1.624852	0.147711	0.029538	0	1.028677	0.005906	0.014769
61	<i>Telecommunications</i>	7142.88	0.307698	3.077028	6.769454	0.615407	0.123079	0	4.285677	0.024622	0.061539
62	<i>Computer programming, consultancy and information service activities</i>	30,628.02	1.317422	13.17424	28.98333	2.634847	0.526974	0	18.34084	0.105400	0.263485
63	<i>Information service activities</i>	8983.37	0.418062	4.180599	9.197322	0.836123	0.167221	0	5.822738	0.033450	0.083610
64	<i>Financial service activities</i>	33,656.12	1.527099	15.27101	33.59622	3.054198	0.610838	0	21.26946	0.122178	0.305423
65	<i>Insurance, reinsurance and pension funding activities auxiliary to financial and insurance activities</i>	3341.46	0.141341	1.413455	3.109614	0.282693	0.056534	0	1.968666	0.011303	0.028272
66	<i>Real estate activities</i>	14,697.01	0.684626	6.846259	15.06177	1.369252	0.273852	0	9.535464	0.054772	0.136920
68	<i>Legal and accounting activities</i>	29,213.18	1.341166	13.41167	29.50568	2.682331	0.536469	0	18.67977	0.107308	0.268228
69	<i>Activities of head offices; management consultancy activities</i>	33,201.34	1.527184	15.27181	33.59799	3.054367	0.610870	0	21.27058	0.122190	0.305433
70	<i>Architectural and engineering activities Scientific research and development</i>	11,319.65	0.500696	5.006993	11.01538	1.001402	0.200282	0	6.973740	0.040056	0.100140
71	<i>Advertising and market research</i>	27,982.46	1.285217	12.85211	28.27466	2.570423	0.514083	0	17.90043	0.102835	0.257040
72	<i>Other professional, scientific and technical activities</i>	2901.39	0.126503	1.265014	2.783025	0.253006	0.050601	0	1.761911	0.010121	0.025300
73	<i>Veterinary activities</i>	4646.82	0.207315	2.073203	4.561048	0.414640	0.082924	0	2.887556	0.016584	0.041466
74	<i>Rental and leasing activities</i>	16,661.29	0.765565	7.655651	16.84243	1.531130	0.306224	0	10.66279	0.061252	0.153116
75	<i>Employment activities Travel agency, tour operator and other reservation service and related activities</i>	1393.82	0.064135	0.641333	1.410936	0.128270	0.025654	0	0.893251	0.005135	0.012827
77	<i>Security and investigation activities</i>	3021.61	0.138468	1.384684	3.046315	0.276936	0.055391	0	1.928590	0.011075	0.027695
78	<i>Services to buildings and landscape activities</i>	21,568.64	0.969140	9.691356	21.32099	1.938271	0.387652	0	13.49812	0.077538	0.193825
79	<i>Office administrative and business support activities</i>	4232.30	0.186956	1.869595	4.113103	0.373923	0.074778	0	2.603963	0.014962	0.037389
80	<i>Education</i>	3945.76	0.180517	1.805169	3.971374	0.361036	0.072207	0	2.514238	0.014445	0.036103
81		33,167.84	1.510959	15.10961	33.24115	3.021927	0.604390	0	21.04467	0.120895	0.302188
82		24,953.83	1.122203	11.22200	24.68842	2.244405	0.448882	0	15.65001	0.089782	0.224439
85		5864.54	0.266942	2.669390	5.872665	0.533874	0.106777	0	3.717933	0.021362	0.053388

Table 2 (continued)

Economic activities (secondary and tertiary sectors NACE 06-96)		Employees (number of workers)	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
86	Human health activities	30,626.92	1,419,382	14,193,85	31,226,47	2,838,774	0.567755	0	19,7692	0.113564	0.113564	0.283871
87	Residential care activities	17,553.48	0,829,054	8,290,491	18,239,09	1,658,098	0.331621	0	11,547	0.066328	0.066328	0.165810
88	Social work activities without accommodation	11,622.45	0,555,196	5,551,936	12,214,24	1,110,383	0.222080	0	7,732,729	0.044421	0.044421	0.1111035
90	Creative, arts and entertainment activities	3116.69	0,143,223	1,432,261	3,150,969	0,286,456	0,057,295	0	1,994,850	0,011,460	0,011,460	0,028,642
91	Libraries, archives, museums and cultural activities	512.70	0,022,215	0,222,139	0,488,700	0,044,431	0,008,888	0	0,309,395	0,001,779	0,001,779	0,004,439
92	Gambling and betting activities	1471.68	0,071,035	0,710,325	1,562,711	0,142,061	0,028,416	0	0,989,337	0,005,684	0,005,684	0,014,203
93	Sports activities and recreation activities	5003.74	0,237,625	2,376,202	5,227,654	0,475,240	0,095,046	0	3,309,573	0,019,010	0,019,010	0,047,522
95	Repair of computers and personal goods	4591.55	0,212,357	2,123,569	4,671,843	0,424,713	0,084,942	0	2,957,700	0,016,994	0,016,994	0,042,471
96	Other personal service activities	29,992.83	1,418,925	16,819,27	31,216,40	7,848,872	0,567,572	0,667	68,013,82	0,113,531	0,113,531	16,209,78
TOT		1,414,382	103,032.7	17,688.72	20,240.95	29,403.86	2413.415	1242.075	52,055.45	5479.702	2023.182	8360.887

Table 3 Hybrid accounts for the Piedmont region including uncertainty according to the insurance approach (2010)

Economic activities (secondary and tertiary sectors NACE 06-96)	Employees (number of workers)	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
06 <i>Extraction of crude petroleum and natural gas</i>	615.86	0	0	0	0	0	0	0	0	0	0
07 <i>Mining of metal ores</i>	1.41	0	0	0	0	0	0	0	0	0	0
08 <i>Other mining and quarrying</i>	1380.86	0.001389	0.040419	7.825984	0.010191	0.001621	0	0.150558	0	0	0.01633
09 <i>Mining support service activities</i>	6.00	0	0	0	0	0	0	0	0	0	0
10 <i>Manufacture of food products</i>	33,636.06	25.32634	248.4339	653.4157	8517.412	13.41989	3.324997	1160.9047	50.973165	38.69790	346.1342
11 <i>Manufacture of beverages</i>	4607.93	3.211941	31.04617	71.84351	555.7646	1.081441	0.197632	98.264577	11.549158	6.501426	24.03412
12 <i>Manufacture of tobacco products</i>	22.08	0.007054	0.057372	0.292491	0.055949	0.004406	0	0.3496276	0.0028928	0.000975	0.031307
13 <i>Manufacture of textiles</i>	22,592.18	8.942748	65.94271	312.6265	66.02429	6.223804	1.069918	364.45456	8.9954263	8.204186	244.1849
14 <i>Manufacture of wearing apparel</i>	10,044.57	7.556252	53.84435	214.8294	108.9939	6.196716	1.405362	336.99058	9.6033199	8.664975	230.8156
15 <i>Manufacture of leather and related products</i>	1207.73	1.000532	7.131164	28.91204	15.97369	0.904018	0.208838	47.474791	1.4617446	1.335909	34.37862
16 <i>Manufacture of wood except furniture</i>	10,907.84	6.898220	88.33934	196.1860	2264.976	3.351228	0.821885	363.3365	23.476678	21.43725	83.82615
17 <i>Manufacture of paper and paper products</i>	6148.86	3.836295	108.1334	894.0432	1300.042	2.662369	1.091768	453.73947	39.635462	33.68415	76.86136
18 <i>Printing and reproduction of recorded media</i>	8698.14	5.030676	75.39805	152.7349	643.9354	3.117239	1.209534	217.55586	7.1726737	5.428056	83.94040
19 <i>Manufacture of coke and refined petroleum products</i>	1340.20	4.012267	98.51071	568.3017	874.7600	5.759545	0.843312	1183.4529	48.782905	4.251886	2430.066
20 <i>Manufacture of chemicals and chemical products</i>	10,539.51	1065.290	151.8153	355.5308	4707.330	2565.651	2.129483	915.769	41.793464	34.46736	1918.747
21 <i>Manufacture of pharmaceutical products</i>	2425.55	2.779998	16.25048	85.47793	138.3209	3.071560	0.865864	168.15685	6.0861758	5.734619	102.5525
22 <i>Manufacture of rubber and plastic products</i>	24,704.26	14.02599	159.0003	436.1566	1838.133	6.085185	2.754708	584.97147	187.41303	80.76886	126.8553
23 <i>Manufacture of other nonmetallic mineral products</i>	13,388.79	27.91119	812.6471	2076.086	521.6826	21.54135	48.45070	5667.069	218.79155	130.5621	1755.694
24 <i>Manufacture of basic metals</i>	11,297.82	39.18846	1766.874	573.1474	1424.038	19.47331	29.46440	1480.523	130.82187	85.29580	884.9042
25 <i>Manufacture of fabricated metal products</i>	56,254.28	24.25443	244.8848	806.1162	506.7045	12.24003	3.699580	920.60774	17.530801	16.48816	190.2329

Table 3 (continued)

		Employees (number of workers)	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
26	Manufacture of computer, electronic and optical products	8459.58	3.584732	28.66219	130.0602	194.1757	2.518678	1.142180	178.70108	5.6249218	4.816306	61.59313
27	Manufacture of electrical equipment	14,156.83	19.85518	108.1649	595.0613	401.2773	22.31410	1.737932	978.02517	26.393331	23.58888	894.1326
28	Manufacture of machinery and equipment	54,011.62	23.45574	267.7286	721.1386	1578.569	10.88134	9.582851	1043.1739	23.113714	21.68360	210.5869
29	Manufacture of motor vehicles	54,824.90	21.03183	246.9727	846.3026	3865.590	11.43962	8.452438	1285.3076	16.502197	14.42158	133.5375
30	Manufacture of other transport equipment	11,290.78	5.191080	60.36928	189.1940	504.5634	2.956434	1.845614	286.62619	4.0995108	3.765222	51.46901
31	Manufacture of furniture	3728.48	2.512857	21.35295	73.10207	1804.465	1.583493	0.237844	101.05296	2.8592439	2.626323	48.09855
32	Other manufacturing	13,496.68	8.781079	99.82488	278.6526	293.1477	4.469524	0.280400	363.79259	13.627674	13.19103	112.3920
33	Repair and installation of machinery and equipment	14,346.34	6.388656	62.17711	204.6761	179.7438	2.777494	0.699278	255.13517	9.4238128	8.295338	37.74229
35	Electricity, gas, steam and air conditioning supply	7552.80	71,701.68	3376.515	8924.446	3068.026	146.4175	1.866061	7139.9712	82.263735	80.73743	500.8344
36	Water collection, treatment and supply	2282.67	1.337894	12.31675	41.35616	28.74054	0.813641	0.130218	56.791963	1.59511	1.491256	22.98758
37	Sewerage	898.31	1674.210	19.43255	147.5726	10.37369	117.8958	1624.165	263.96766	8.1847859	7.229707	302.0075
38	Waste collection, treatment and disposal activities	10,322.19	104,561.1	376.8276	512.1385	402.2769	288.4553	67.27486	2295.2323	68.40318	67.95985	302.0293
39	Remediation activities, other waste management services	192.29	0.141225	1.000127	4.144996	3.276086	0.665947	0.027783	8.3284704	0.689365	0.674413	4.926175
41	Construction of buildings	35,439.28	21.64072	185.1943	652.6125	396.7063	13.79984	2.308415	908.91202	23.663764	7.892171	402.2065
42	Civil engineering	7043.53	4.930439	48.12277	149.0600	106.7880	2.699874	0.421076	207.02471	5.1401503	4.823023	75.23942
43	Specialized construction activities	97,505.12	54.68332	478.3595	1688.651	3495.333	33.05433	5.071497	2283.0695	57.214397	19.13382	893.7651
45	Wholesale and retail trade and repair of motor vehicles and motorcycles	34,233.57	2.412890	24.12893	64.25913	350.5076	0.965162	0	33.606772	0.1930563	0.193056	0.584175
46	Wholesale trade, except of motor vehicles and motorcycles	82,094.74	5.785359	57.85349	154.0730	11.57069	2.314148	0	80.578362	0.4628842	0.462884	1.400653
47	Retail trade, except of motor vehicles and motorcycles	145,694.40	10.40544	104.0545	277.1135	3252.592	4.162178	0	144.9271	0.8325415	0.832541	2.519214

Table 3 (continued)

Economic activities (secondary and tertiary sectors NACE 06–96)	Employees (number of workers)	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)
49 Land transport and transport via pipelines	44,416.29	462.5345	17,398.72	6813.373	3798.460	193.7505	51.26830	47,560.877	7514.7951	2335.332	51,75317
50 Water transport	92.50	0.008119	0.081193	0.216230	0.016238	0.003247	0	0.1130859	0.0006496	0.000649	0.001965
51 Air transport	393.08	0.257450	617.1533	98.26014	251.7415	0.833924	0.003712	33.142896	7.0077383	6.672462	30.96132
52 Warehousing and support activities for transportation	24,080.48	1.767131	17.67136	47,06161	3.534276	0.706852	0	24.612666	0.1413876	0.141387	0.427830
53 Postal and courier activities	13,110.32	0.933908	9.339098	24.87150	1.867816	0.373557	0	13.007497	0.0747281	0.074728	0.226099
55 Accommodation	9499.23	0.701351	7.013522	18.67811	1.402700	0.280546	0	9.7684315	0.0561214	0.056121	0.169804
56 Food and beverage service activities	70,899.98	5.063416	50.63421	134.8468	10.12684	2.023364	0	70.523317	0.4051233	0.405123	1.225884
58 Publishing activities	4141.43	0.279249	2.792466	7.436768	81.70991	0.111700	0.458596	6.9820288	0.0306359	0.030635	0.067606
59 Motion picture and television program production	1646.84	0.113233	1.132334	3.015586	0.226467	0.045287	0	1.5771163	0.0090525	0.009052	0.027417
60 Programming and broadcasting activities	1692.28	0.112260	1.122619	2.989728	0.224521	0.044898	0	1.5635901	0.0089776	0.008977	0.027175
61 Telecommunications	7142.88	0.467702	4.677083	12.45579	0.935420	0.187081	0	6.5142299	0.0374254	0.037425	0.113232
62 Computer programming, consultancy	30,628.02	2.002482	20.02485	53.32933	4.004967	0.801001	0	27.890607	0.1602086	0.160208	0.484813
63 Information service activities	8983.37	0.635454	6.354510	16.92307	1.270908	0.254175	0	8.8505618	0.0508451	0.050845	0.153842
64 Financial service activities	33,656.12	2.321191	23.21193	61.81704	4.642381	0.928474	0	32.32959	0.1857117	0.185711	0.561978
65 Insurance, reinsurance and pension funding	3341.46	0.214839	2.148452	5.721690	0.429693	0.085932	0	2.9923723	0.0171817	0.017181	0.052020
66 Activities auxiliary to financial and insurance activities	14,697.01	1.040631	10.40631	27.71365	2.081263	0.416256	0	14.493907	0.0832539	0.083253	0.251934
68 Real estate activities	29,213.18	2.038572	20.38574	54.29046	4.077143	0.815432	0	28.393259	0.1631082	0.163108	0.493544
69 Legal and accounting activities	33,201.34	2.321320	23.21316	61.82030	4.642638	0.928522	0	32.33129	0.1857293	0.185729	0.561998
70 Activities of head offices; management consultancy activities	11,319.65	0.761058	7.610630	20.26831	1.522132	0.30443	0	10.600086	0.060886	0.060886	0.184259
71 Architectural and engineering activities	27,982.46	1.953529	19.53521	52.02537	3.907043	0.781406	0	27.208659	0.1563093	0.156309	0.472954
72 Scientific research and development	2901.39	0.192285	1.922821	5.120766	0.384570	0.076914	0	2.6781053	0.0153848	0.015384	0.046553
73 Advertising and market research	4646.82	0.315119	3.151269	8.392328	0.630254	0.126044	0	4.3890857	0.0252081	0.025208	0.076299

Table 3 (continued)

	<i>Employees (number of workers)</i>	CH ₄ (t)	CO (t)	CO ₂ (1000 t)	COV (t)	N ₂ O (t)	NH ₃ (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO ₂ (t)	
74	<i>Other professional, scientific and technical activities</i>	16,661.29	1.163659	11.63659	30.99007	2.327318	0.465461	0	16.207449	0.0931036	0.093103	0.281734
75	<i>Veterinary activities</i>	1393.82	0.097485	0.974826	2.596123	0.194971	0.038994	0	1.3577416	0.0078062	0.007806	0.023601
77	<i>Rental and leasing activities</i>	3021.61	0.210472	2.10472	5.605219	0.420944	0.084195	0	2.9314582	0.0168353	0.016835	0.050959
78	<i>Employment activities</i>	21,568.64	1.473094	14.73086	39.23062	2.946172	0.589232	0	20.517144	0.1178582	0.117858	0.356638
79	<i>Travel agency, tour operator and other reservation service and related activities</i>	4232.30	0.284174	2.841784	7.568109	0.568363	0.113663	0	3.9580242	0.0227423	0.022742	0.068796
80	<i>Security and investigation activities</i>	3945.76	0.274387	2.743857	7.307329	0.548774	0.109755	0	3.8216429	0.0219565	0.021956	0.066434
81	<i>Services to buildings and landscape activities</i>	33,167.84	2.296657	22.96661	61.16372	4.593329	0.918673	0	31.987908	0.1837607	0.183760	0.556027
82	<i>Office administrative and business support activities</i>	24,953.83	1.705749	17.05745	45.42669	3.411496	0.682300	0	23.757617	0.1364687	0.136468	0.412969
85	<i>Education</i>	5864.54	0.405752	4.057474	10.80570	0.811488	0.162301	0	5.6512588	0.0324702	0.032470	0.098234
86	<i>Human health activities</i>	30,626.92	2.157461	21.57465	57.45672	4.314937	0.862988	0	30.049184	0.1726183	0.172618	0.522324
87	<i>Residential care activities</i>	17,553.48	1.260163	12.60154	33.55992	2.520309	0.504065	0	17.55144	0.1008198	0.100819	0.305091
88	<i>Social work activities without accommodation</i>	11,622.45	0.843899	8.438944	22.47421	1.687782	0.337562	0	11.753748	0.0675199	0.067519	0.204304
90	<i>Creative, arts and entertainment activities</i>	3116.69	0.217699	2.177037	5.797784	0.455413	0.087088	0	3.0321722	0.0174202	0.017420	0.052702
91	<i>Libraries, archives, museums and cultural activities</i>	512.70	0.033768	0.337651	0.899208	0.067536	0.013510	0	0.4702809	0.0027053	0.002705	0.008168
92	<i>Gambling and betting activities</i>	1471.68	0.107974	1.079694	2.875389	0.215932	0.043192	0	1.5037927	0.0086398	0.008639	0.026133
93	<i>Sports activities and recreation activities</i>	5003.74	0.361190	3.611827	9.618884	0.722365	0.144470	0	5.0305515	0.0288954	0.028895	0.087442
95	<i>Repair of computers and personal goods</i>	4591.55	0.322782	3.227825	8.596191	0.645565	0.129113	0	4.4957041	0.0258319	0.025831	0.078147
96	<i>Other personal service activities</i>	29,992.83	2.156766	26.23807	57.43818	12.97680	0.86271	1.04052	106.10156	0.1725681	0.172568	25.28725
TOT		1,414,382	179,869.8	27,914.11	31,027.17	47,649.13	3551.001	1875.553	80,387.3	8679.2785	3110.445	12,708.16

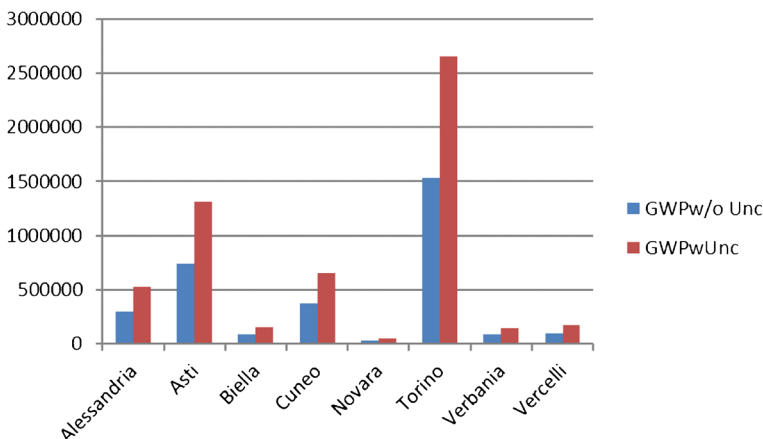
Table 4 Environmental themes without (w/o) and with (w) uncertainty

	GWP (w/o)	ACID (w/o)	TOFP (w/o)	GWP (w)	ACID (w)	TOFP (w)
<i>Alessandria</i>	298,295	219	20,959	523,293	351	34,634
<i>Asti</i>	733,052	89	5882	1,316,406	145	9804
<i>Biella</i>	87,624	137	3522	156,618	229	6303
<i>Cuneo</i>	372,166	323	27,884	648,388	508	44,699
<i>Novara</i>	24,610	38	4381	45,117	65	7631
<i>Torino</i>	1,536,027	661	61,029	2,653,132	1050	98,778
<i>Verbania</i>	81,627	70	5375	143,823	110	8589
<i>Vercelli</i>	94,659	100	7532	169,294	159	12,228

uncertainty. In provinces such as Novara, Asti, and Biella, the increase of the estimate added by uncertainty is larger than in the other provinces; this can be explained by the fact that the uncertainty in NO_x and SO_2 emissions is very high in the manufacturing activities in which these three provinces specialize. Inventory data for the four provinces need to be further processed by taking uncertainty into account, using more sophisticated techniques.

Finally, the estimates for TOFP are presented in Fig. 3. Novara and Biella are once again among the provinces where uncertainty increases the most. In addition to CH_4 and NO_x , the uncertainty of VOC is especially high for SNAP 03 (i.e., combustion in manufacturing industries), as that of CO is for SNAP 04-06 (i.e., production processes, extraction and distribution of fossil fuels and geothermal energy, solvents, and other product usage); this is explained by the presence of a variety of manufacturing activities (from food transformation to machinery and material production). Considering the importance of Novara as a crossroads for commercial traffic, uncertainty due to pollutants connected to transport activities (SNAP 07) plays a major role. Once again, it would be advisable to consider uncertainty when extracting inventory data for Novara, Biella, and Torino; this initial screening demonstrates that a robustness issue could occur.

The same message expressed in Table 4 and shown in Figs. 1, 2, and 3 is further illustrated in Fig. 4, where the percentage increase in data with uncertainty (compared to the data without uncertainty) is simultaneously presented for the eight provinces. For the three indicators,

**Fig. 1** GWP with and without uncertainty in Piedmont provinces (2010)

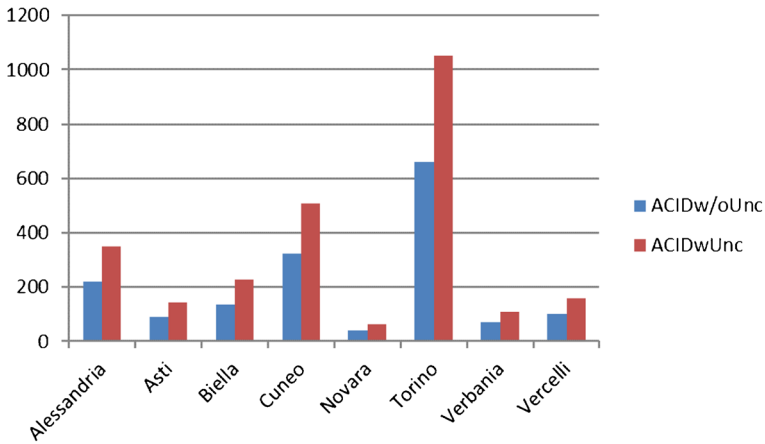


Fig. 2 Acidification with and without uncertainty in Piedmont provinces (2010)

Novara and Biella show an increase close to and greater than 0.80, while in the case of Torino, the range is between 0.50 and 0.60.

The analysis of estimates with and without uncertainty for environmental themes highlights how the difference between the results from analyzing emission data with and without uncertainty depends to a great extent on the pollutants emitted by specific economic activities. The same typology of pollutant can have a different uncertainty coefficient for different economic activities; thus, it is important to analyze the economic sectors together with the emissions data. In fact, taking into account the prevailing economic activities in a region, a province, or a municipality helps one understand the extent to which uncertainty might impact estimates provided to the final decision maker.

Finally, uncertainty might matter because of the high weight of emissions in a particular part of the territory compared to other parts (as in the case of Torino) or because of the specialization in production activities where the uncertainty coefficient is higher (as is the case mainly in Biella and Novara). Considering the environmental themes, in-depth analyses are be

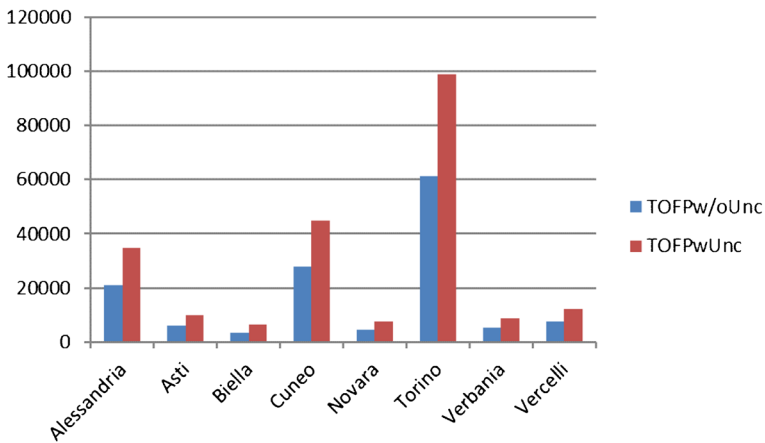


Fig. 3 Tropospheric ozone formation potential (tons/year) with and without uncertainty in Piedmont provinces (2010)

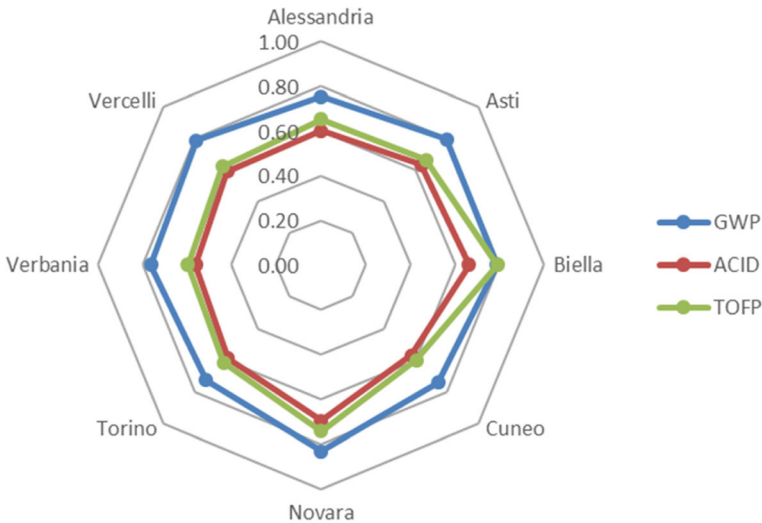


Fig. 4 Estimate increase with and without uncertainty for the three environmental themes in Piedmont provinces (2010)

needed for these three provinces, though such analysis might require a further processing of inventory data, for example, by considering medians of the min-max/uncertainty intervals or by applying the Monte Carlo technique (as done in La Notte et al. 2018).

3.3 The shift-share analysis

Environmental themes consider the calculation of uncertainty in absolute values. By using shift-share analysis, we consider relative values by relating emissions to the number of employees in each sector. Here we consider two cases with two different levels of aggregation. Considering the outcomes for the previous section, the provinces of Biella and Torino are presented as showcases.

As a first case, in a previous application (La Notte et al. 2015), different groups of manufacturing activities were agglomerated from the secondary sector, and only transport activity was taken into account from the tertiary sector. The two summary tables provide information about the following:

- Industry mix: a negative value indicates that in the Biella province, those sectors that employ more workers pollute less; the negative sign occurs for all pollutants except NH_3
- Efficiency (productivity differential): a negative value indicates that in the Biella province, economic activities that employ more workers pollute less than at the regional level; however, this does not happen for CH_4 , CO , NH_3 , or PM , meaning that there is room for improvement in eco-efficiency technology
- Allocative component: a negative value indicates that the Biella province specializes in economic activities that pollute less, the negative sign occurs only for CH_4 and PM

It is unusual that the allocative component records a different sign compared to the industry mix and the differential component. This component indicates whether and to what extent the

system productively specializes in the fields where it carries out a comparative advantage of efficiency. Despite its efficiency and sector structure, Biella does not productively specialize in what concerns the sectors that mostly emit CO₂, COV, N₂O, and SO₂.

Table 5 shows a different policy message, whether uncertainty is considered or not, especially for what concerns the “efficiency.” Improvement in ecological efficiency is also needed for NO_x and SO₂. On the other hand, in terms of the allocative component, NO_x turns out to be neutral.

The same kind of analysis can be applied for the province of Torino (Table 6). The summary table provides information about:

- Industry mix: a negative value indicates that in the Torino province, those sectors that employ more workers pollute less; the negative sign only occurs for COV, N₂O, and NH₃
- Efficiency: a negative value indicates that in the Torino province, economic activities that employ more workers pollute less than at the regional level; the negative sign occurs for all pollutants
- Allocative component: a negative value indicates that the Torino province specializes in economic activities that pollute less; the negative sign occurs for CH₄, CO, CO₂, NO_x, and PM₁₀

When taking uncertainty into account, (i) some pollutants that were positive (SO₂ in the industry mix) without uncertainty can become neutral with uncertainty and (ii) some pollutants that were neutral without uncertainty can become positive (NH₃ in the allocative component) or negative (PM_{2.5} in the allocative component) with uncertainty.

As the second case, in the current application, we have considered every single economic activity from the secondary and the tertiary sectors to avoid the possibility that selecting only a few economic sectors and aggregating different economic sectors in different ways might affect the final result.

The counter-intuitive case of the allocative component exhibiting a sign which does not follow the logic of combining the signs of both industry mix and efficiency can be explained as follows. Let us consider, for example, the allocative effect of CO in the Province of Torino (Table 8). There are sectors, such as food manufacture (10), other nonmetallic mineral products

Table 5 Shift-share summary table for the province of Biella (sectorial aggregation)

	Without uncertainty			With uncertainty		
	Industry mix	Efficiency	Allocative component	Industry mix	Efficiency	Allocative component
CH ₄	-0.0758	0.0314	-0.0255	-0.1423	0.0601	-0.0477
CO	-0.0145	0.0015	0.0004	-0.0242	0.0036	0.0003
CO ₂	-0.0169	-0.0092	0.0048	-0.0261	-0.0110	0.0055
COV	-0.0237	-0.0252	0.0121	-0.0404	-0.0403	0.0192
N ₂ O	-0.0023	-0.0035	0.0021	-0.0029	-0.0044	0.0026
NH ₃	0.0004	0.0007	0.0	0.0008	0.0008	0.0
NO _x	-0.0406	-0.0022	0.0017	-0.0629	0.0031	0.0
PM ₁₀	-0.0042	0.0041	-0.0016	-0.0070	0.0075	-0.0029
PM _{2.5}	-0.0015	0.0010	-0.0003	-0.0025	0.0018	-0.0006
SO ₂	-0.0081	-0.0001	0.0029	-0.0114	0.0041	0.0027

Table 6 Shift-share summary table for the province of Torino (sectorial aggregation)

	Without uncertainty			With uncertainty		
	Industry mix	Efficiency	Allocative component	Industry mix	Efficiency	Allocative component
CH ₄	0.0422	-0.0102	-0.0021	0.0799	-0.0210	-0.0043
CO	0.0041	-0.0068	-0.0005	0.0070	-0.0117	-0.0011
CO ₂	0.0053	-0.0092	-0.0004	0.0081	-0.0144	-0.0005
COV	-0.0030	-0.0161	0.0050	-0.0055	-0.0247	0.0085
N ₂ O	-0.0009	-0.0032	0.0010	-0.0009	-0.0039	0.0012
NH ₃	-0.0001	-0.0011	0.0	-0.0002	-0.0018	0.0001
NO _x	0.0105	-0.0278	-0.0007	0.0169	-0.0413	-0.0015
PM ₁₀	0.0011	-0.0029	-0.0002	0.0019	-0.0049	-0.0004
PM _{2.5}	0.0003	-0.0010	0.0	0.0006	-0.0016	-0.0001
SO ₂	0.0001	-0.0117	0.0003	0.0	-0.0166	0.0006

(23), basic metals (24), and air transport (51), where the structural component (the difference between the provincial level and the regional level) records a negative sign. The emission differential effect in these sectors is very high (negative), and this combination produces a multiplying effect that finally generates a positive outcome. When calculating the industry mix, the negative structural component of sectors 10, 23, and 24 is overcome by the positive number of other sectors, such as transport (49) and electricity (35).

By looking at Tables 7 and 8, we can track differences with and without uncertainty on the numerical values processed but not differences on the sign; what is recorded as negative remains negative, and what is recorded as positive remains positive. A sector decomposition performed in this case study actually confirms that the differences generated by previous applications were indeed the outcome of how the sectors were selected and combined. In order to understand why, in relative values, the difference in estimates with and without uncertainty does not emerge, we must look at another source of information in the [Supplementary Material \(S1\)](#), that is, the economic structure of each province and the relationship of that structure with the economic structure of the region as a whole. In doing this, we see percentages that range from a maximum of 3–4% (with a few exceptions; e.g., Biella records 17% for the textile industry) to an average of 0.0002% for most provinces, across all secondary and tertiary

Table 7 Shift-share summary table for the province of Biella (sectorial disaggregation)

	Without uncertainty			With uncertainty		
	Industry mix	Efficiency	Allocative component	Industry mix	Efficiency	Allocative component
CH ₄	-25.4749	16.17959	-14.0065	-45.4091	31.77092	-25.9841
CO	-5.21863	1.202757	-0.94431	-8.28292	1.80811	-1.35217
CO ₂	-4.19504	-5.94423	1.356209	-6.39043	-8.34349	1.739199
COV	-8.556	-8.34362	3.456894	-13.7577	-13.1204	5.354072
N ₂ O	-0.78484	-1.23588	0.485702	-1.11199	-1.70365	0.585068
NH ₃	1.697746	-0.17218	-1.02774	2.584142	-0.30623	-1.55181
NO _x	-12.5059	12.63781	-16.3736	-20.0684	20.48908	-25.3188
PM ₁₀	-1.58246	3.934662	-2.8519	-2.51286	5.89572	-4.19243
PM _{2.5}	-0.5457	1.167358	-0.93969	-0.85372	1.757962	-1.37665
SO ₂	-1.42295	25.93455	-26.4463	-1.93614	40.41795	-41.2763

Table 8 Shift-share summary table for the province of Torino (sectorial disaggregation)

	Without uncertainty			With uncertainty		
	Industry mix	Efficiency	Allocative component	Industry mix	Efficiency	Allocative component
CH ₄	10.58172	-1.10695	0.084839	18.49756	-2.85096	0.004077
CO	0.444589	-3.35012	0.133173	0.748834	-5.24579	0.191431
CO ₂	0.044845	-3.37161	0.499766	0.075549	-5.2274	0.74754
COV	-2.31701	-5.55402	1.9421	-3.96343	-8.96331	3.159275
N ₂ O	-0.48027	-1.36045	0.506492	-0.66822	-1.93632	0.712986
NH ₃	0.011834	-0.51249	-0.0013	0.01822	-0.77002	-0.00222
NO _x	0.090914	-11.2496	1.184073	0.391321	-17.1357	1.657581
PM ₁₀	0.113506	-1.26473	0.004137	0.190191	-1.99301	0.002881
PM _{2.5}	0.011034	-0.42621	0.02412	0.027179	-0.62618	0.032047
SO ₂	-1.06442	-5.02011	1.042209	-1.6205	-7.54972	1.585403

sectors. The fact that there is no remarkable difference among the provinces is exactly what affects the results with respect to relative values.

This happens because we have not included the primary sector in the distribution of weights. If we could do so, the distribution in terms of employees and value added would considerably change the structural shape of provinces such as Asti, Alessandria, Cuneo, Novara, and Vercelli. The regional structure, which is heavily affected by the province of Turin, will differ from the provincial structure, where agriculture plays an important role. In principle, a tool such as shift-share analysis could be extremely useful for this kind of application; however, we want to highlight the fact that the way it is applied does indeed matter. In our case study, the outcomes are misleading, because the entire productive structure is not fully represented. When relative values are used, it is thus important not only to choose the tool properly but, most of all, to use it properly. When properly used, the robustness of inventory data in shift-share analysis may play an important role in providing policymakers with the right signals in term of actions to be undertaken. A determination of whether the main cause of emissions (e.g., CO₂ emission for the climate agendas of mayors or PM₁₀ and PM_{2.5} emissions for the health of citizens) lies in the production structure of the provincial economy or lies in the lack of eco-technologies will lead to very different policies.

4 Discussion and conclusions

Taking uncertainty into account could have some effects on policy use, not only when looking at compliance rules and emission trading on the national scale but also when looking at local policy action at regional and provincial levels. But taking uncertainty into account can be time- and resource-consuming, especially for small administrations. This paper shows how to screen whether and in which cases the assessment of uncertainty should be undertaken, because such assessment generates different outcomes for policymaker decisions. Hybrid accounting tables were built considering data drawn from the emission inventory at regional and provincial levels, and uncertainty was added throughout the approach, borrowed from the insurance sector. Once the accounting tables (without and with uncertainty) were available, two sets of policy tools were applied: environmental profiles through environmental indicators, which considered the absolute values of the emissions reported in regional-NAMEA, and the shift-share analysis, which related emissions values to socioeconomic values. The former set of tools showed a

remarkable difference between data without uncertainty and data with uncertainty, while the latter tool did not show any difference.

The results obtained with this application allowed a few principles to be generalized. First, the consideration of uncertainty makes a difference in one's choosing between tools that provide results either in absolute terms (such as the indicators related to the environmental themes) or in relative terms (such as a shift-share analysis). The former tools do indeed record a quantitative difference that can be quite large, while the latter tool might reduce the difference. If not properly used, this tool could also nullify the differences, as happened in our application. Users must be aware of the different peculiarity of each tool and must interpret the outcomes with caution. There is a risk of underestimating the role of uncertainty in data processing and thus of not highlighting the need for an in-depth analysis.

Another important principle to consider is the importance of linking the economic side with the environmental side, since consideration of the size and economic meaning of each sector provides crucial input in understanding how significant it could be to include uncertainty in the estimate of the data; each pollutant can result in a different uncertainty, according to different production processes, and thus can produce a different result with respect to economic activity. Different economic activities can also play diverse roles in specific territorial contexts. The more disaggregated the focus of the analysis is, the greater the worth of the economic and environmental data at the local level is and the more reliable the information.

For example, when we consider the region as a whole, we record the strong footprint of the province of Turin in terms of population and economic activities and thus of the emitted pollutants. Yet the peculiarities of provinces such as Biella, specializing in the textile sector, or Verbania, specializing in the extractive industry and energy, disappear. The possibility of specifically linking certain pollutants to those economic activities arises through analysis at the provincial level. And this linkage becomes much more complicated at the regional level, unless regional estimates result from the aggregation of provincial estimates.

In methodological terms, an insurance-based approach applied as an initial screening tool can be very useful in selecting where and how to concentrate the attention when further data refinements are required in terms of uncertainty. This can be the case particularly when budget and time constraints might affect the possibility of performing a complete analysis for all pollutants and all territorial contexts.

The same insurance-based approach can be refined for activities and pollutants that need to be further analyzed. Adding the full uncertainty amount calculated through the uncertainty coefficient systematically overestimates the impact of uncertainty on current estimates; to avoid this systematic overestimation, it is possible to apply Monte Carlo techniques with appropriate distribution in order to calculate a likely estimate of the emitted pollutants. Once a more sophisticated procedure has developed, the insurance-based approach could be applied at the national level (i) by applying the procedure directly to the national air emission inventory and (ii) by applying the procedure to the regional inventories and then aggregating them. The latter solution can be more difficult and time-consuming, but it would leave open the possibility of accessing local scale details that would otherwise be missed on a national scale.

Acknowledgements We thank the editors and three anonymous reviewers for their constructive comments, which helped us to improve the manuscript.

We thank Gianluigi Truffo (Regione Piemonte Direzione Ambiente, Sistema Informativo Ambientale) for providing the air emission data of the Piedmont Region and for his technical support.

References

- Charkovska N, Halushchak M, Bun R, Jonas M (2015) Uncertainty analysis of GHG spatial inventory from the industrial activity: a case study for Poland. In: Proceedings of the 4th International Workshop on Uncertainty in Atmospheric Emissions. Kraków, Poland. 7–9 October 2015
- Charkovska N, Bun R, Danylo O, Horabik-Pyzel J, Jonas M (2018) High resolution spatial distribution and associated uncertainties of greenhouse gas emissions from the agricultural sector. (This issue)
- Dalmazzone S, La Notte A (2013) Multi-scale environmental accounting: methodological lessons from the application of NAMEA at sub-national levels. *J Environ Manag* 130:405–416
- De Boo A, Bosch P, Gorter CN, Keuning SJ (1993) An environmental module and the complete system of national accounts. In: Franz A, Stahmer C (eds) Approaches to environmental accounting. Physica, Heidelberg
- De Haan M, Keuning SJ (1996) Taking the environment into account: the NAMEA approach. *Rev Income Wealth* 42:131–148
- Esteban J (2000) Regional convergence in Europe and the industry mix: a shift-share analysis. *Reg Sci Urban Econ* 30(3):353–364
- European Environment Agency (2013) EMEP/EEA air pollutant emission inventory guidebook 2013. Technical guidance to prepare national emission inventories 23 pp <https://www.eea.europa.eu/publications/emep-eea-guidebook-2013> Cited 8 February 2018
- European Environment Agency (2016) EMEP/EEA air pollutant emission inventory guidebook 2016. Technical guidance to prepare national emission inventories Technical report 9/2009 24 pp <https://www.eea.europa.eu/publications/emep-eea-guidebook-2016> Cited 8 February 2018
- Eurostat (2015) Manual for air emissions accounts 2015 edition. Luxembourg: <http://ec.europa.eu/eurostat/documents/3859598/7077248/KS-GQ-15-009-EN-N.pdf/ce75a7d2-4f3a-4f04-a4b1-747a6614eb3>. Cited 8 February 2018
- Gillenwater M, Sussman F, Cohen J (2007) Practical policy applications of uncertainty analysis for national greenhouse gas inventories. *Water Air Soil Pollut Focus* 7(4–5):451–474
- Halushchak M, Bun R, Jonas M, Topylko P (2015) Spatial inventory of GHG emissions from fossil fuels extraction and processing: an uncertainty analysis. In: Proceedings of the 4th International Workshop on Uncertainty in Atmospheric Emissions. Kraków, Poland. 7–9 October 2015
- IPCC—Intergovernmental Panel on Climate Change (2006) IPCC guidelines for national greenhouse gas inventories. Volume I: general guidance and reporting. IPCC, Geneva
- ISTAT (2009) Contabilità Ambientale e Pressioni sull'Ambiente Naturale: dagli schemi alle realizzazioni. *Annali di Statistica* 138(XI). Vol 2
- Jonas M, Nilsson S (2007) Prior to economic treatment of emissions and their uncertainties under the Kyoto Protocol: scientific uncertainties that must be kept in mind. *Water Air Soil Pollut Focus* 7(4–5):495–511
- Jonas M, Gusti M, Jęda W, Nahorski Z, Nilsson S (2010) Comparison of preparatory signal analysis techniques for consideration in the (post-) Kyoto policy process. *Clim Chang* 103(1–2):175–213
- Keuning SJ (1993) An information system for environmental indicators in relation to the national accounts. In: de Vries WFM, den Bakker GP, Gircour MBG, Keuning SJ, Lenson A (eds) The value added of national accounting statistics in the Netherlands. Voorburg, Heerlen, pp 287–305
- La Notte A, Dalmazzone S (2012) Feasibility and uses of the NAMEA-type framework applied at local scale: case studies in North-Western Italy. In: Costantini V, Mazzanti M, Montini A (eds) Hybrid economic-environmental accounts. Routledge studies in ecological economics. Taylor & Francis Group, London
- La Notte A, Tonin S, Nocera S (2015) How uncertainty of air emission inventories impacts policy decisions at sub-national level. A shift-share analysis undertaken in Piedmont (Italy). In: Proceedings of the 4th International Workshop on Uncertainty in Atmospheric Emissions. Kraków Poland, 7–9. October 2015
- La Notte A, Tonin S, Lucaroni G (2018) Assessing direct and indirect emissions of greenhouse gases in road transportation, taking into account the role of uncertainty in the emissions inventory. *Environ Impact Assess Rev* 69:82–93
- Leontief W (1970) Environmental repercussions and the economic structure: an input-output analysis. *Rev Econ Stat* 52:262–271
- Lieberman D, Jonas M, Nahorski Z, Nilsson S (eds) (2007) Accounting for climate change uncertainty in greenhouse gas inventories—verification, compliance and trading. Springer, Netherlands
- Marland E, Cantrell J, Kiser K, Marland G, Shirley K (2014) Valuing uncertainty part I: the impact of uncertainty in GHG accounting. *Carbon Manag* 5(1):35–42
- Mazzanti M, Montini A, Zoboli R (2007) Territorial productive structure and environmental efficiency indicators through regional NAMEA data. *Economia delle fonti di energia e dell'ambiente* 1:1–31
- Nocera S, Tonin S, Cavallaro F (2015) Carbon estimation and urban mobility plans: opportunities in a context of austerity. *Res Transp Econ* 51:71–82

- Tonin S, La Notte A, Nocera S (2016) A use-chain model to deal with uncertainties. A focus on GHG emission inventories. *Carbon Manag* 7(5–6):347–359
- Topylko P, Halushchak M, Bun R, Oda T, Lesiv M, Danylo O (2015) Spatial greenhouse gas inventory and uncertainty analysis: a case study of electricity generation and fossil fuels processing. In: *Proceedings of the 4th International Workshop on Uncertainty in Atmospheric Emissions*. Kraków, Poland. 7–9 October 2015
- White T, Jonas M, Nahorski Z, Nilsson S (eds) (2011) *Greenhouse gas inventories: dealing with uncertainty*. Springer Netherlands, Dordrecht