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ORIGINAL PAPER

Extended statistical entropy analysis for the evaluation of nitrogen budgets in Austria

A. P. Sobańtka · S. Thaler · M. Zessner · H. Rechberger

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Abstract Extended statistical entropy analysis (eSEA) is used to evaluate the nitrogen (N) budgets of two Austrian catchments, the Wulka and the Ybbs, and of entire Austria. The eSEA quantifies the extent of N dispersion in the environment. The results from the eSEA are compared to the corresponding N use efficiencies (NUEs). Application of the eSEA reveals that the Ybbs catchment, compared to the Wulka catchment leads to a greater extent of N dispersion, primarily as a result of increased losses of N compounds to the atmosphere and in leachates to the groundwater. The NUE in the Wulka catchment, at 63 %, is substantially higher than that in the Ybbs catchment, at 43 %, and confirms a more efficient N use in Wulka. Furthermore, it is shown that the adoption of a healthy, balanced diet, as defined by the German Nutrition Society, changes the N budget of Austria in a way that significantly reduces the dispersion of N. Decreased N losses to the atmosphere and to the groundwater are primarily responsible for this result. The national NUE of Austria responds only moderately to the adoption of such a diet increasing from 48 to 53 % and leads to statistically insignificant results if the uncertainty of the input data is taken into account. This study demonstrates the effectiveness of eSEA for the evaluation of N budgets in agricultural regions and suggests that statistical entropy can serve as a reliable agri-environmental indicator to support decisions regarding nutrient management.

Keywords Agri-environmental indicators · Emissions from agriculture · Evaluation methods · Nitrogen budgets · Optimized nutrition · Statistical entropy

Introduction

Human activities have significantly increased the amount of reactive nitrogen (N_r: all N compounds except N_2) in the global N cycle, particularly in industrialized countries (Galloway et al. 2004; Smil 1999; Vitousek et al. 1997). The amount of N_r continues to increase on a global scale, primarily as a result of agricultural activities (Galloway et al. 2004; Gruber and Galloway 2008; Nielsen 2006; Sutton et al. 2011). In fact, agriculture has been identified as the major source of increased N_r emissions to both the atmosphere and surface and groundwater (Bouwman et al. 1997; Mosier et al. 1998; Van Drecht et al. 2003; Chen et al., 2013). Smil (1999) has found that crop production is the principle cause of the anthropogenic alteration of the N cycle (Smil 1999). The gap between the creation of N_r and the N that is needed for human nutrition represents the N surplus (Galloway et al. 2003). This surplus N accumulates in the atmosphere and hydrosphere, causing environmental problems ranging from eutrophication to global acidification and ultimately contributing to climate change (Camargo and Alonso 2006; Bouwman et al. 2005; Gruber and Galloway 2008; Tilman 1999; Vitousek et al. 1997). In addition, the N cycle interacts with other major biogeochemical cycles and can have serious consequences,

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A. P. Sobańtka (✉) · S. Thaler · M. Zessner · H. Rechberger
Centre for Water Resource Systems, Vienna University of Technology, Karlsplatz 13/E222, 1040 Vienna, Austria
e-mail: sobantka@waterresources.at

A. P. Sobańtka · S. Thaler · M. Zessner · H. Rechberger
Institute for Water Quality, Resource and Waste Management, Vienna University of Technology, Karlsplatz 13/226, 1040 Vienna, Austria

particularly for the carbon cycle (Gruber and Galloway 2008; Vitousek et al. 1997). Efforts have been made to reduce N_r emissions with the help of environmental policies and tools such as the N footprint calculator. These initiatives should help to raise public awareness of the environmental impacts caused by N (Leach et al. 2011).

In the USA, it has been shown that intervention in combustion processes, manure and fertilizer application, cropland management, N use efficiency (NUE), and wastewater treatment could reduce the anthropogenic N_r load to the environment by 20 % (Galloway and Theis 2009). The NUE measures the extent to which the total N originally introduced into the system has been transferred into the end product. Europe can generally be considered an excess N area. Even though in Great Britain the ammoniacal N flux was reduced from 1974 to 2005 the total dissolved N flux increased due to NO_3^-, NO_2^-, and dissolved N_{org} (Worrall et al. 2009). In the Netherlands, approximately 40 % of all N input is lost to the environment (Kroeze et al. 2003). In Sweden, human activities have been found to disperse a major part of the N flow to the air and to water bodies (Danius and von Malmborg 2001). An N balance was first presented for Austria for the year 1986 (Atzmüller et al.1990). This N budget was then evaluated from the perspective of the Austrian economy (Dissemond et al. 1991). Subsequently, an N balance for the entire agricultural area of Austria was calculated for 1985–1996 in accordance with the OECD standards (OECD 1996), and an N surplus of 30 kgN/ha was detected (Götz 1998). The N fluxes in Austria over the period 1950–1995 demonstrate how anthropogenically initiated agricultural activities have interfered with the natural N cycle and the extent to which they have affected the environment (Gaube 2002). The most recent data on N budgets for Austria are available for the years 2001–2006 (Thaler et al. 2011). Based on these data, the N budgets have been recalculated based on a diet recommended by the German Nutrition Society (DGE 2004). Such a diet would be beneficial to human health and would allow N to be used more efficiently. As a consequence of this change, the area needed for the production of animal-based foodstuffs, the nutritional requirements for food production, the impact on the hydrosphere, the energy demand, and the emissions of CO_2 equivalents would be significantly reduced (Fazeni and Steinmüller 2011; Thaler et al. 2011). These potential effects have also been predicted at both European and global scales (Sutton et al. 2011; Stehfest et al. 2009; Steinfeld et al. 2006; Westhoek et al. 2011; Westhoek et al. in prep.).

The environmental impact of the N surplus is classically assessed based on life cycle impact assessment (LCIA). LCIA includes impact categories such as the global warming potential, eutrophication, and acidification (Basset-Mens and van der Werf 2007; Cederberg and Flysjö 2004; De Vries and de Boer 2010; Haas et al. 2005; van der Werf and Petit 2002). The EcoX indicator, for example, was defined based on LCIA. This indicator reveals the overall environmental impact of cropping systems, and it considers different chemical compounds and several impact categories, including resource depletion, land use, climate change, toxicity, acidification, and eutrophication (Brentrup et al. 2003; Brentrup et al. 2004a, b). Alternatively, the N surplus can be estimated and interpreted as an indicator of the environmental impact of cropping systems (Carpani et al. 2008; Ondersteijn et al. 2001; Schröder et al. 2003). However, an estimate of the N surplus provides no information about the types of N compounds, their amount released to the environment, or the proportion of N lost to the atmosphere, to the hydrosphere, or to the soil. Optionally, the NUE is calculated to indicate the efficiency of agricultural production relative to total N. Moreover, the NUE provides an indication of the N surplus that will be dispersed in the environment. The worldwide NUE for cereal production has been estimated at approximately 33 % (Raun and Johnson 1999). The global NUE of industrialized countries has been increasing steadily, from 48 % in 1970 and 49 % in 1995 to its current value of 60 %, and it is expected to reach 62 % in 2030 with the potential for further improvement (Bouwman et al. 2005; Cassmann et al. 2002; Liu et al. 2010). Despite their usefulness in facilitating the more efficient use of N and, therefore, in reducing the effect of N on the environment, neither the N surplus nor the NUE can quantify the dispersal of various N compounds resulting from agricultural activities. However, the reported NUEs show that a significant amount of N is lost to the environment. The effects of management practices on the risk of N loss to the environment can be modeled with the Nitrogen Loss and Environmental Assessment Package model (NLEAP) (Delgado et al. 2006, a, b). Based on the NLEAP model, a N trading tool (NTT) has been introduced in the USA. The NTT can help users view the potential monetary rewards or drawbacks associated with variations in their agricultural practice (Gross et al. 2008). However, NLEAP does not evaluate these N losses. The monetary benefit resulting from the reduction in N emissions to the environment can also be quantified with cost-benefit analysis (CBA). An example of a CBA reveals the need to prioritize NO_x and NH_3 abatement over the abatement of N_2O emissions (Brink and van Grinsven 2011). N balances per se are among the environmental indicators for agriculture and represent one of ten different criteria for the evaluation of ecological sustainability (Austrian Ecology Organization 2011; Com(2001)144); OECD 2001a, 2001b). However, the focus of such N balances is the emissions of single N compounds, such as NO_3^- leached into the groundwater or

NH_3 emissions to the atmosphere. For this reason, N balances fail to provide a holistic assessment of all N losses. The statistical entropy analysis (SEA) quantifies the distribution of a substance (e.g., a heavy metal) among different material flows (e.g., waste, fly ash, wastewater) before and after a process (e.g., waste incineration). The change in the distribution of the substance then indicates the concentrating power relative to the extent of dilution (dispersion) of the particular process (Rechberger and Brunner 2002). To date, SEA has been primarily applied to the field of waste and resource management to assess the efficacy of different processes in recovering substances such as heavy metals (Kaufman et al. 2008; Rechberger 2001a, b, 2012; Rechberger and Graedel 2002; Yue et al. 2009). SEA has subsequently been extended to enable its application to processes in which the specification of chemical compounds is highly relevant, as is the case for N. Such a system can, for example, specify the N budget of a farming region. Statistical entropy, applied as a measure of concentration and dilution, can potentially serve as an agri-environmental indicator (Sobańtka et al. 2012). In a separate study, the advantages of extended SEA (eSEA) over the traditional N removal rate for the evaluation of the N removal performance of wastewater treatment systems have been demonstrated (Sobańtka and Rechberger 2013).

The purpose of the present paper is to introduce eSEA as a new agri-environmental evaluation method, using N budgets in Austrian farming regions as an example. The study will compare two different catchments. Additionally, the N budgets for the state-of-the-art nutritional conditions in Austria are compared to those corresponding to a healthy balanced diet recommended by the German Nutrition Society.

Materials and methods

The investigated catchments

The catchments that are the subject of this work are located in Austria. Animal husbandry and crop farming are the agricultural activities occurring in these catchments. N is processed through these catchments in the form of various N compounds including NH_4^+, NO_3^-, NH_4NO_3, $CO(NH_2)_2$, N_2, NH_3, N_2O, NO_x, and N_{org} (i.e., proteins contained in animal-based and plant-based foodstuffs) and are distributed by different material flows (e.g., fertilizer, seeds, compost, water, air). Food products based on N_{org} are extracted, and by-products (gaseous N emissions such as N_2O or NH_3 or waterborne emissions such as NO_3^-) are released into the atmosphere and hydrosphere. N can also be stored in the soil. Extensive data sets are available for two Austrian catchments and for two nutritional alternatives, the nutritional state-of-the-art for all Austria (ASN) and the optimized diet for Austria (AON) according to the German Nutrition Society (Thaler et al. 2011). The data are expressed as average annual values over the period 2001–2006. To apply eSEA, the following additional assumptions are required: Animal feedstuff is assumed to contain 50 % dry matter, and chemical fertilizer is assumed to represent a mixture of 94 % NH_4NO_3 and 6 % $CO(NH_2)_2$ with a total N content of 40 %. The value of deposition is assessed from the precipitation data for the period 2001–2006 (Parajka et al. 2007). Sludge is estimated to include a total N content of 1.5 %. A dry matter content of 10 % is assumed for forage and a 50 % dry matter content for farm fertilizer. The N_{org} representing protein in animal-based products is not differentiated from the N_{org} in plant-based products.

The data for the two Austrian regions considered in the study are then normalized to 1 kg N anthropogenic input. This input includes N from animal feedstuffs, sludge, compost, chemical fertilizer, and seeds. In this way, the regions can be compared to each other. The data for the ASN system are normalized to 4.4 kgN/cap/years, which corresponds to the actual N uptake in Austria. The data for the AON system are normalized to an N uptake of 4.0 kgN/cap/years. This value corresponds to the reduced N uptake resulting from the optimized diet defined by the German Nutrition Society. Both systems, ASN and AON, are thus normalized to produce sufficient N for human demand and can be compared to one another on this basis.

The Wulka and the Ybbs catchments

The Wulka catchment is located in the federal state of Burgenland, in eastern Austria, and covers 38,333 ha. The area used for agriculture during 2001–2006 was 19,349 ha. A total of 57 kgN/ha/years (39 kgN/cap/years) are processed in Wulka. Overall, 64 % of the anthropogenic N enters the region via chemical fertilizer, and 28 % of the anthropogenic N results from animal feedstuffs. The dominant production of N in the region is represented by plant-based goods. The NUE is 63 %. Consequently, the N surplus in Wulka is 37 %, i.e., 21 kgN/ha/years. The N budget is shown in Fig. 1, where the individual N compounds that are contained in the different material flows are also specified.

The Ybbs catchment is located in the federal state of Lower Austria, in northern Austria, and covers 110,468 ha. The area used for agriculture during 2001–2006 was 38,107 ha. The Ybbs catchment experiences an N turnover of 138 kgN/ha/years (76 kgN/cap/years). In all, 44 % of the introduced N comes from chemical fertilizer and 53 % from animal feedstuffs. In Ybbs, the animal-based products are dominant. Less N is generated in the form of plant-

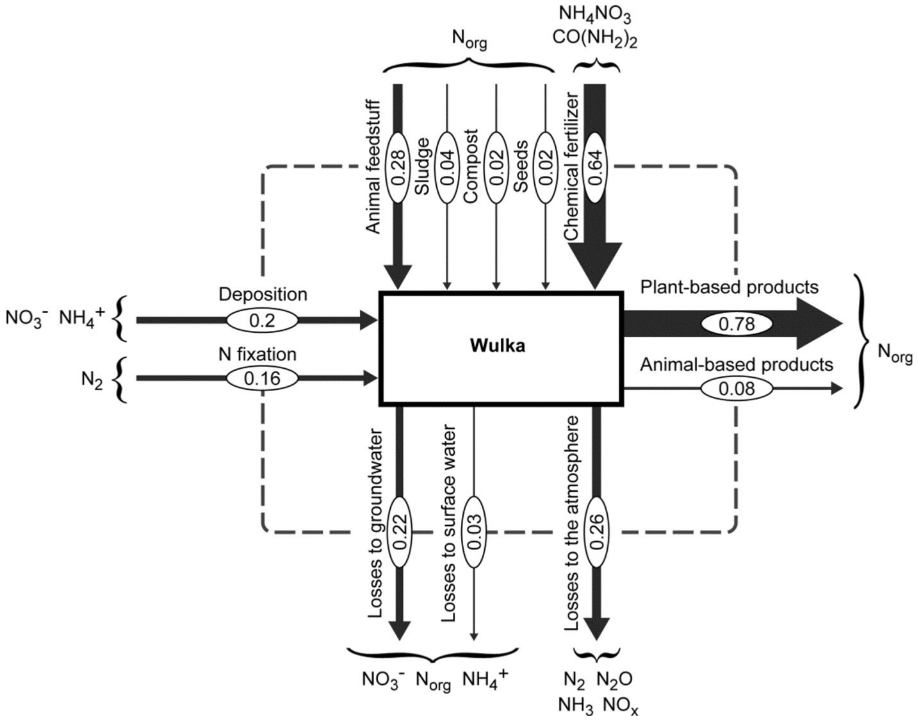


Fig. 1 Nitrogen budgets of the Wulka catchment in Burgenland (eastern Austria) including the individual nitrogen compounds; data are normalized to 1 kg N anthropogenic input

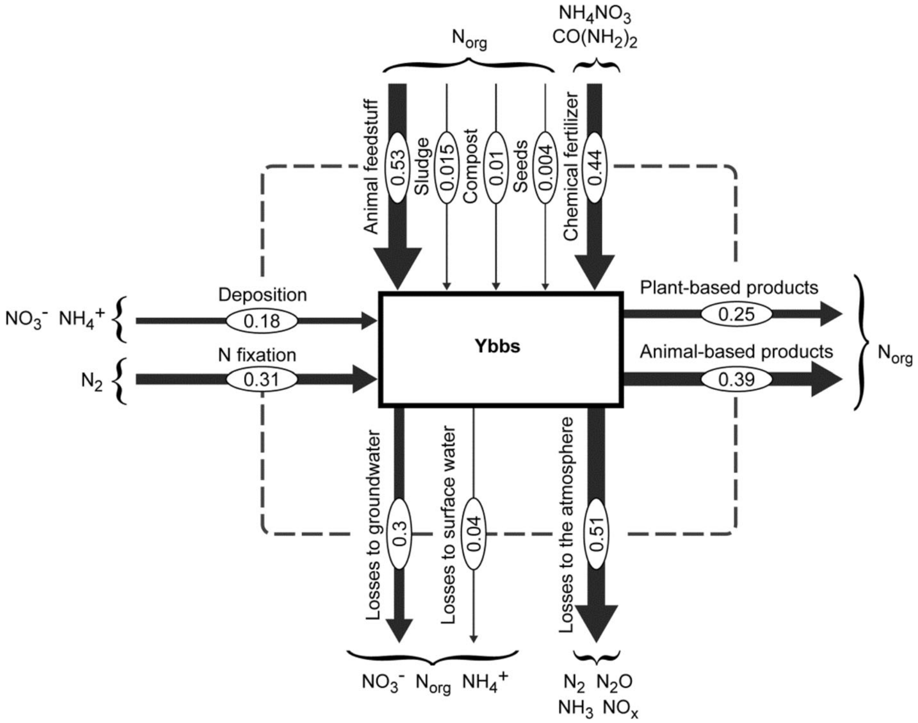


Fig. 2 Nitrogen budgets of the Ybbs catchment in Lower Austria (northern Austria) including the individual nitrogen compounds; data are normalized to 1 kg N anthropogenic input

based products in Ybbs than in Wulka. In Ybbs, the N emissions to groundwater are greater and the N emissions to the atmosphere substantially higher. The NUE is 43 %. Consequently, the N surplus in Ybbs is 57 %, i.e., 79 kgN/ha/years. The N budget is shown in Fig. 2.

The "Austria state-of-the-art nutrition" and the "Austria optimized nutrition" systems

The estimated total area of Austria is 8,387,100 ha. Of this area, 222,775 ha was used for agriculture during

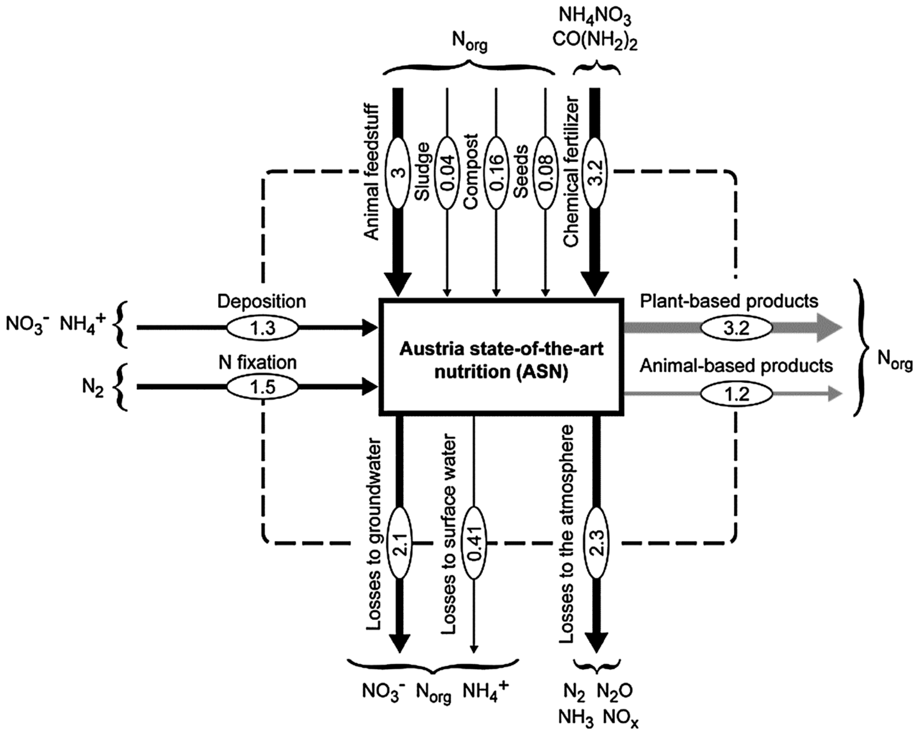


Fig. 3 Nitrogen budgets for the ASN system; flows are normalized to a nitrogen uptake of one person per year (4.4 kgN/cap/years)

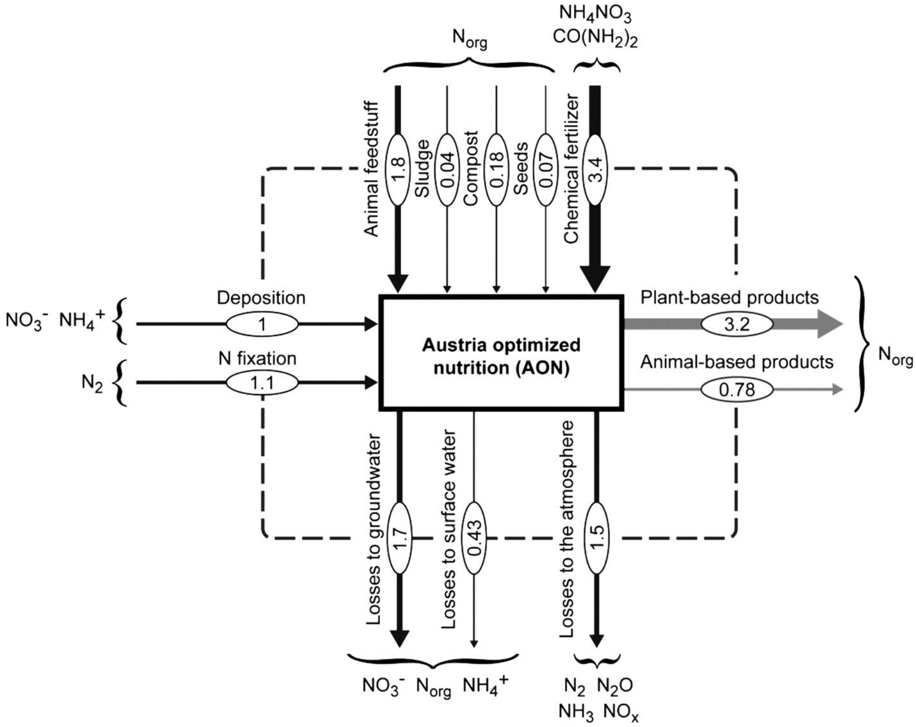


Fig. 4 Nitrogen budgets for the AON system; flows are normalized to an optimal nitrogen uptake of one person per year (4.0 kgN/cap/years)

2001–2006. The N turnover is 99 kgN/ha/years or 39 kgN/cap/years. The NUE is 48 %. The N surplus in Austria is 52 %, i.e., 51 kgN/ha/years. The N budget is shown in Fig. 3.

The German Nutrition Society has recommended a nutrition plan that would primarily benefit human health (DGE 2004). Under this nutrition plan, the N budgets in Austria would change (cf. Figure 4). The total N turnover would be reduced to 71 kgN/ha/years (corresponding to 28 kgN/cap/years). In all, 35 % less N would be converted to animal-based goods. Therefore, 40 % less N would be needed in the form of animal feedstuffs. Consequently, the gaseous N losses would decrease by 35 %. The N losses to groundwater would decrease by 19 %. The NUE for the AON system would increase to 53 %. Consequently, the N surplus would decrease to 33 kgN/ha/years. The N budget is shown in Fig. 4.

Extended statistical entropy analysis (eSEA)

Statistical and extended statistical entropy analysis (SEA and eSEA, respectively) assess the concentrating power and accordingly the extent of dilution of substances throughout a defined process or system (Rechberger and Brunner 2002; Sobańtka et al. 2012). Although SEA can only be applied to chemical elements, eSEA can be used for systems where the specification of chemical compounds is of particular importance. Such a system can consist of the N budget in a farming region or the N balance of a wastewater treatment plant (Sobańtka et al. 2012; Sobańtka and Rechberger 2013). The data that are needed to perform an eSEA are the material flows, the concentrations of the N compounds in the particular material flows, and the natural background concentrations in the environment. It is preferable to select the natural background concentrations characteristics of the unstressed atmosphere and hydrosphere to optimally reflect the diluting impact. The statistical entropy is calculated for the input to the region and for the output of the N compounds that leave the region. The change in statistical entropy, ΔH, then indicates the extent of the dilution (dispersion) of N compounds in the system. The supporting information presented for this section of the paper provides greater detail on the computation of the statistical entropy.

The major advantage of the eSEA is that it provides a holistic assessment of the N performance of a region by quantifying the dissipation of N. All N compounds are included, and their impact on the environment is reflected by the individual diluting masses. For example, the emission of N_2 makes no contribution to statistical entropy because the atmosphere consists primarily of N_2. In contrast, the emission of NH_3 will cause dilution because little NH_3 is present in the atmosphere; therefore, more air (a higher dilution mass) is needed to dilute the NH_3 until it reaches its low background concentration. The eSEA is especially useful for complex systems that include several material flows and numerous N compounds. Another advantage of the eSEA is that weighting factors for different compounds are not required. The eSEA also meets the standards defined by van der Werf and Petit for the assessment of the environmental impact of agriculture at the farm level (2002): The dilution of N compounds indicates the potential harm to the environment caused by the N compounds, the statistical entropy indicator is effect-based, the results can be expressed per unit product, threshold values can be set by defining maximum and minimum entropy production scenarios, and the results can generally be validated through the use of other evaluation methods. The disadvantages of eSEA include its relatively high data requirements and the small number of applications currently available for comparing the results. Furthermore, eSEA calculates the hypothetical diluting masses in a way that disregards the actual amount of, for example, water available in the catchment. In this respect, the impact on the groundwater in the Wulka catchment is more critical than the impact in the Ybbs catchment because the regeneration of the groundwater is significantly lower in Wulka. Finally, eSEA addresses only the ecological dimension of the problem, disregarding the social and economic dimension.

Results and discussion

Evaluation of the N performance of the Wulka and the Ybbs catchments and of the Austria state-of-the-art-nutrition (ASN) and the Austria optimized nutrition (AON) systems

In this study, the N performances of the Wulka and Ybbs catchments of the entire ASN and of the AON systems are assessed with eSEA. The numerical results are shown in Table 1 and are illustrated in Fig. 5. To better understand the meaning of the entropy values, two contrasting hypothetical reference situations are presented: If all N is transformed to food products in the catchment, entropy production is minimized ($H_{\min}$); in contrast, entropy generation is maximized ($H_{\max}$) if all N is emitted to the environmental compartment with the lowest natural background concentration [this outcome would correspond to the emission of N_{org} to groundwater of very high water quality according to the Austrian Water Act (Austrian Water Act 2010b)].

The calculated entropy values are standardized by division by the maximum entropy value. These standardized results range between zero and one. The entropy increase ΔH is also reported. The input of N into the catchments translates into a certain level of entropy because the N compounds are introduced via different material flows in different concentrations. Even if all of the N could be transferred to food products, an entropy increase would still occur because the N is more dispersed in the plant- and animal-based products than in the input material flows. However, the entropy increase is significantly higher if the real losses to the atmosphere and to the hydrosphere are also incorporated.

The entropy increase ΔH is significantly higher for the Ybbs catchment (335 %) than for the Wulka catchment

Table 1 Results from eSEA on the nitrogen performance and the NUEs of the Wulka catchment, the Ybbs catchment, the ASN system, and the AON system

	H_{IN}	H_{min}	H_{OUT}	H_{max}	$H_{IN,rel}$	$H_{min,rel}$	$H_{OUT,rel}$	ΔH	NUE
WULKA	4.27	6.43	12.0	40.4	0.11	0.16	0.30	180 %	63 %
YBBS	4.63	8.04	20.1		0.11	0.20	0.50	335 %	43 %
ASN	4.02	6.59	17.2		0.10	0.16	0.42	327 %	48 %
AON	4.01	6.93	13.6		0.10	0.17	0.34	240 %	53 %

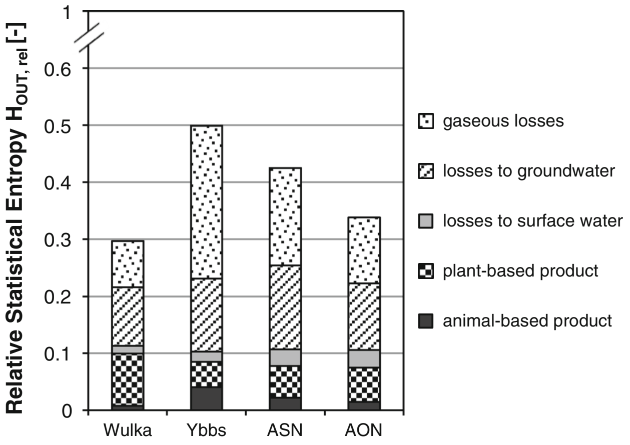


Fig. 5 eSEA results for the nitrogen performances of the Wulka catchment, the Ybbs catchment, the ASN system, and the AON system

(180 %). This result shows that the N anthropogenically applied to the system is diluted to a greater extent in Ybbs than in Wulka. Figure 3 shows that the principal contributors to the poor N performance of the Ybbs catchment are the gaseous losses to the atmosphere. The amount of N emitted to the atmosphere by the Ybbs catchment is almost twice that emitted by Wulka. The entropy contribution of the gaseous N losses is, however, 3.3-fold higher for Ybbs than for Wulka, based on the various N compounds (e.g., NH_3, N_2O, and NO_x), their individual background concentrations, and the various diluting masses. N losses to both the surface water and the groundwater also marginally produce an increased entropy value in the Ybbs catchment. The N that is converted into the products is not diluted; however, the creation of the products also generates entropy to a certain extent. The entropy proportion associated with the products is in the range of the input entropy ($H_{rel} = 0.1$) for the Wulka catchment and is slightly less than the corresponding input entropy for the Ybbs catchment. This difference is due primarily to the lower concentration of N associated with plant-based products. Accordingly, Ybbs achieves a higher concentration of N relative to the food products, but this result is achieved at the cost of the high dilution of N compounds in the atmosphere (cf. Figure 2). In general, the entropy production associated with the food products is higher for Wulka than for Ybbs, but the entropy generation due to the losses of N to the environment is disproportionately higher for Ybbs. An explanation of this outcome cannot be derived directly from the available data. However, according to literature findings, the production of animal-based foods might be the most likely explanation for the greater losses from the Ybbs catchment (Thaler et al. 2011; Fazeni and Steinmüller 2011; Stehfest et al. 2009; Steinfeld et al. 2006; Sutton et al. 2011, Westhoek et al. 2011; Westhoek et al. in prep.). It may as well be possible to change the N management in the Ybbs catchment in such a way that the production of animal-based goods remains constant while the emissions to the atmosphere decrease. The NUE indicates a higher efficiency for Wulka (63 %) than for Ybbs (43 %). However, changes in the gaseous N losses (N_2, NH_3, N_2O, NO_x) or the N emissions to surface water and groundwater (NO_3^-, NH_4^+, N_{org}) would not be reflected in the NUE. The disadvantages of the NUE are discussed in more detail in “Emission scenarios” section.

The entropy increase, ΔH, is significantly higher for the ASN system (327 %) than for the AON system (240 %). Both systems produce sufficient N to meet the human demand. Overall, however, the AON system dilutes N to a lesser extent than the ASN system. Figure 3 shows that reduced gaseous losses and decreased emissions to groundwater are primarily responsible for the improved N performance of the AON system. The N losses to surface water and the associated entropy proportions are comparable in the two systems (cf. Figs. 3, 4). The ASN system transfers 1.5 times as much N to animal-based foodstuffs and emits 1.5 times as much N to the atmosphere as the AON system. Consequently, the entropy proportion of the animal-based foods in the ASN system is 1.5-times greater than the corresponding entropy proportion in the AON system, whereas the entropy production associated with the plant-based products is slightly lower (6.3 %). The NUE analysis confirms higher efficiency for the AON system (53 % compared to 48 % for the ASN system). However, the response of the NUE to the alteration of the N budgets is less significant than that of the statistical entropy (see section “Sensitivity analysis”).

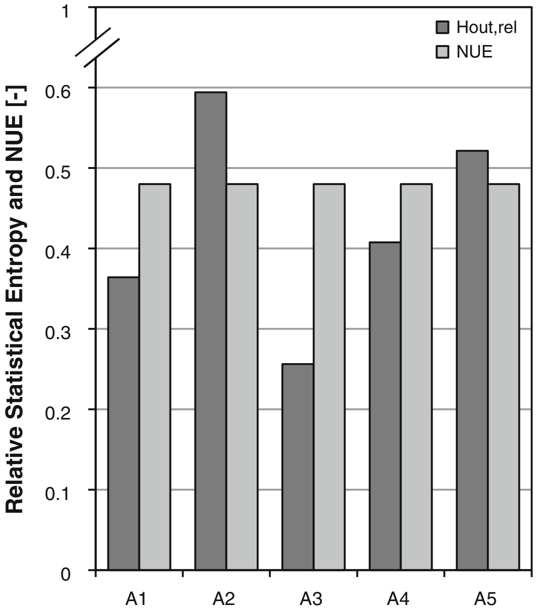


Fig. 6 eSEA results and NUEs for the hypothetical emission scenarios based on the ASN system

To present a comprehensive discussion of the N budgets of both regions, the ecological rucksack of the N input flows should also be considered. This would include the exploitation of the resources needed for the production and transport of the particular material flows. The ecological rucksack of animal feedstuffs is more complex and can be significantly larger than that one of the chemical fertilizers, for instance. The ASN system requires 1.9 times more animal feedstuffs than the AON system. Therefore, the total input of fertilizer for the ASN alternative would be greater. However, the different ecological rucksacks associated with the material flows that are responsible for the N input are not considered in this evaluation. Moreover, the detailed nutritional requirements and the energy demands of both regions are not incorporated. Furthermore, the particular hydrological and geological conditions associated with the catchments can limit the resulting N performance and should therefore be considered in the discussion. These considerations are not addressed in this paper because the focus of the study is the application of eSEA to the assessment of N performance rather than a comprehensive study of the catchments.

Emission scenarios

To emphasize the benefits that favor the use of eSEA rather than NUE, several hypothetical emissions scenarios are developed. These scenarios are based on the ASN system and will be evaluated with both the eSEA and NUE approaches. Scenario A1 is defined by the original N budgets in the ASN system. In both scenarios A2 and A3, the total N losses to the atmosphere are kept constant, but the emissions of the different N compounds (N_2, NH_3, NO_x and N_2O) are allowed to vary. In scenario A2, the emissions of NH_3, NO_x, and N_2O are each increased by 50 %, whereas N_2 is reduced accordingly. In scenario A3, only N_2 is emitted to the atmosphere. In both scenarios A4 and A5, the N losses to surface water and groundwater are kept constant, but the emissions of NO_3^-, NH_4^+, and N_{org} are modified. For scenario A4, it is assumed that only NO_3^- is lost to surface water and groundwater. In scenario A5, the N losses to the hydrosphere are assumed to occur only in the form of N_{org} only. The relative entropy values for the output distribution of the N compounds and the NUEs are shown in Fig. 6.

Figure 6 clearly shows that only eSEA responds to the presented hypothetical emission scenarios. The NUE remains the same for all scenarios because it only considers the total N in the product and in the input. However, the additional emissions of NH_3, NO_x, and N_2O to the atmosphere in scenario A2, for example, are clearly less desirable. In turn, it is favorable if all N losses to the atmosphere occur in the form of N_2 (cf. scenario A3). The natural background concentration of NO_3^- in water bodies of very high water quality is significantly higher than the concentration of N_{org}. As a result, the discharge of NO_3^- produces less entropy and, accordingly, less dilution than the discharge of N_{org}. The environmental impact of NO_3^- on water bodies is also demonstrably lower than the impact of N_{org} (Austrian Water Act 2010a; Guinée et al. 2002; Westgate and Park 2010). These results demonstrate that NUE might not be appropriate for a comprehensive assessment of N budgets, and the evaluation of these budgets may benefit from the use of eSEA.

Sensitivity analysis

A sensitivity analysis for the eSEA results and the NUEs is presented based on a Monte Carlo simulation. Many input data show an uncertainty of approximately ±10 % (Danius 2002). Due to missing information about the quality of the available data used in this work, the relative uncertainty is assumed to have values of 10 or 20 %. These two cases are analyzed on the assumption of normally distributed data. The mean values for the changes in statistical entropy and NUE along with the corresponding standard deviations are shown in Figs. 7 and 8.

The results in Figs. 7 and 8 show that the change in statistical entropy is significantly lower for the Wulka catchment than for the Ybbs catchment even at relative data uncertainties of 20 %. Based on a relative data uncertainty of 10 %, the AON system still achieves an improvement in N performance. The certainty that the AON system will result in improved N performance is

Fig. 7 Results for eSEA obtained from a sensitivity analysis based on relative uncertainty levels of the input data of 10 % (*left*) and 20 % (*right*)

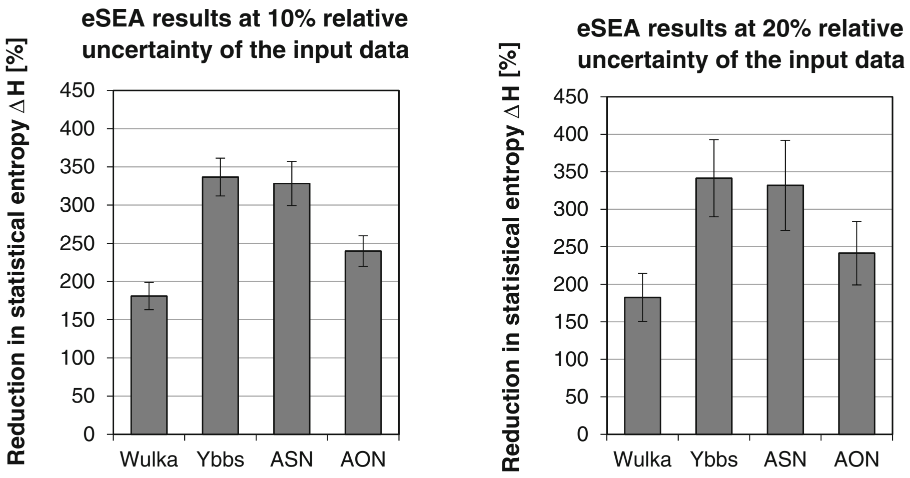
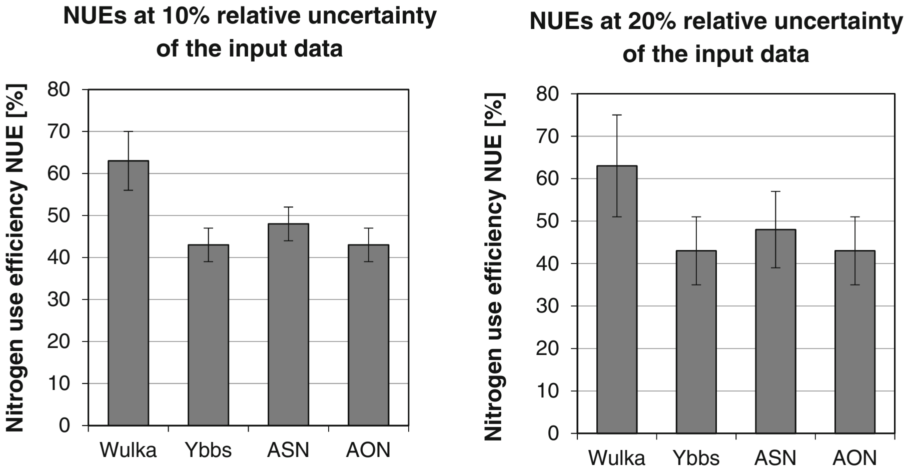


Fig. 8 NUEs obtained from a sensitivity analysis based on relative uncertainty levels of the input data of 10 % (*left*) and 20 % (*right*)



slightly reduced if a relative data uncertainty of 20 % is assumed. The NUE approach indicates that the N performance of the Wulka catchment is superior to that of the Ybbs catchment even if the data are associated with a 20 % relative uncertainty. However, greater efficiency of the AON system is no longer significant if an input data uncertainty of 10 or 20 % is considered. Based on these results, the NUE value is considerably less meaningful. However, it has previously been demonstrated that the AON system is more advantageous for the environment in many respects than the ASN system (Fazeni and Steinmüller 2011; Thaler et al. 2011).

Conclusion

In this study, the usefulness of statistical entropy as an agri-environmental indicator is tested by applying eSEA to the N budgets of two Austrian regions, the Wulka and the Ybbs catchments, and to the ASN and AON systems. The results show that the N performance of the Wulka catchment is superior to the N performance of the Ybbs catchment, primarily as a result of the lower level of N emissions of the former to the atmosphere and to groundwater. The use of the optimized nutrition system (AON) defined by the German Nutrition Society changes the Austrian N budgets so that the total N is dispersed to a lesser extent. These changes improve the Austrian N performance. However, for the significance of the results, the uncertainty in the data must be considered. The NUE for the Wulka catchment is greater than that for the Ybbs catchment; however, if the expected uncertainty of the input data is considered, the AON system is not clearly more efficient than the ASN system. Furthermore, variations in the N compounds released to the atmosphere and in those discharged to surface water and groundwater are not addressed by the NUE calculations. Therefore, we conclude that statistical entropy is a more comprehensive indicator for assessing nutrient balances than NUE. Finally, the authors recommend eSEA for the assessment of the N budgets of other systems for further testing of the approach and after successful validation propose the integration of eSEA results in decision-making processes regarding N management strategies.

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