Alternate Mid-Point Terrestrial Acidification Characterization Factors Considering Acid Strength

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Abstract: Current life cycle mid-point impact assessment practice uses several different mid-point indicators for terrestrial acidification (TA). More than a few methods use a mid-point category indicator of mole proton equivalents. The present research shows that the current mid-point TA indicators—the proton equivalent methods—are not precise as the acid strength is not considered. First, the inventory result for one million tonnes solid steel manufacturing output is calculated based on literature. Then the acidifying compounds—which can form acids—are identified. Then the following are proposed: formed acids, the number of protons formed, mole protons per gram acidifying compound and eventually the product of the acidity constant of acids formed and mole protons per gram acidifying compound. After, three different mid-point TA indicators are multiplied with the inventory result: i) the proton equivalents method excluding carbon dioxide, ii) the proton equivalents method including carbon dioxide, and finally iii) the proton equivalents/acidity constant method including carbon dioxide. The results show that the present acid strength based mid-point indicator for TA improves the understanding and can act as a sensitivity check of state-of-the-art mid-point TA results. Carbon dioxide emitted to air is insignificantly contributing to mid-point TA indicator results which are based on proton release and acid strength. Hydrogen chloride emitted to air is one of the main contributors to mid-point TA indicator results which are based on proton release and acid strength.

By using the acid strength as basis for the TA mid-point indicator, a more universal method for comparing the TA potential for gases is achieved. The next step is to clarify how acidity constant based mid-point TA indicators work with normalization of acidification such as distance to target methods and environmental cost accounting methods.

Keywords: Acids, Acidity constant, Hydrogen chloride, Hydrogen fluoride, Life cycle mid-point impact assessment, Mid-point indicator, Soil acidification.

1. INTRODUCTION

Life cycle assessment (LCA) is a standardized methodological framework for estimating and assessing some of the possible environmental and health impacts attributable to the life cycle of a product or technology, such as acidification, eutrophication, and acute and chronic health effects [1]. LCA offers a way to do model based estimations of environmental impacts. LCA is especially useful when one wants to estimate the probability of the environmental loadings of the next technology being lower than state-of-the-art. The mathematical framework for the linear attributional LCA model—until the normalization of the mid-point indicators—is well-known [2, 3], but is repeated from [3] for the sake of clarity in Eqs. 1 to 6:

\[
g = BA^{-1}f
\]  

(1)

\[
g = \begin{pmatrix} g_1 \\ \vdots \\ g_i \\ \vdots \\ g_n \end{pmatrix} \quad \text{for } i = 1,2,\ldots,n
\]  

(2)

\[
l_{i(j)} = g^T_i k_{i(j)} \quad \text{for } i = 1,2,\ldots,n
\]  

(3)

\[
l_j = \sum_{i=1}^{n} l_{i(j)} \quad \text{for } j = 1,2,\ldots,q
\]  

(4)

\[
l_j(w) = \frac{l_j}{w_j}
\]  

(5)

\[
EB = \sum_{j=1}^{q} l_j(w)
\]  

(6)

where

\[g = \text{vector of environmental loadings, e.g. shown in Table 5.}\]

\[B = \text{flow of environmental loadings, e.g. hydrogen fluoride in Table 2.}\]

\[A = \text{flow of products and materials, e.g. pig iron in Table 3.}\]

\[f = \text{demand vector, e.g. one million tonnes of solid steel in Table 5.}\]

\[f_u = \text{functional unit of } f\]

\[i = \text{environmental loading.}\]

\[i = \text{environmental impact category.}\]
Acidification is known as natural and anthropogenic acid deposition in rivers, lakes, soils, and oceans and as it could be an environmental problem, it is one of the most prominent mid-point impact categories in LCMPIA. Acidification is a mid-point category and base saturation in soil - expressed as molve proton equivalents - is a mid-point category indicator of Acidification. Very often so called sulfur dioxide equivalents [2] are used in mid-point TA instead of proton equivalents, e.g. in Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) which was developed to assist in impact assessment for sustainability metrics, LCA, industrial ecology, process design, and pollution prevention [5]. Clearly such sulfur dioxide equivalents have been developed from proton equivalents by normalizing all values to sulfur dioxide.

So far TA is the most common form of acidification included in LCA, however recently oceanic acidification was proposed [6]. The actual TA - the end-point TA - is generally caused by nitrogen oxides and sulfur dioxide [7]. However rainfall, root respiration, decomposition of organic matter, fertilizer use [8-10], and oxidative weathering also contribute to TA via free protons. The mechanism for TA in soils is that increased concentrations of protons and strong acid anions (e.g. Cl and NO\(_3\)) lead to increased rates of leaching of base exchangeable cations – such as Ca\(^{2+}\), Mg\(^{2+}\), K\(^{+}\) or Na\(^{+}\) - and to the associated acidification of soils. This causes the soil pH to fall below 7 which in turn increases the percentage of toxic - acid exchangeable cations - Al\(^{3+}\) and protons relative to other cations [11]. Moreover, it is well-known that carbon dioxide cause different sorts of acidification [12]. For example carbon dioxide has the ability to cause soil acidification via respiration of plant roots [13] and the gas should be included in the development of the next generation of mid-point TA methods due to the relatively large amounts emitted. Andrae [14] rudimentarily attempted to address the problem for aquatic acidification, but failing to recognize the acidity constants, proposed that carbon dioxide would dominate mid-point aquatic acidification. Current mid-point TA practices in LCMIA only include a very limited view of the soil acidification mechanism, namely the number of protons that can theoretically be released when an acidifying compound is hydrolyzed or oxidized. On this basis it is obviously possible to improve the current proton based mid-point TA indicator. This research will prove that the current methods are incorrect compared to the present proposal of introducing the acid strength - of the acid formed - into the model. Hydrogen fluoride is the strongest evidence of the limitation of current practice.

The acid dissociation constant, K\(_a\), (also known as acidity constant, or acid-ionization constant) is a quantitative dimensionless measure of the strength of an acid in solution – by which \(k_{i(j)}\) in equation 3 can be enhanced.

The new method for assessing midpoint TA is applied to a specific system of steel production processes in Italy [15].
The hypotheses for steel manufacturing described in literature are:

- Carbon dioxide is – if included - the main contributor to mid-point TA indicator results which are based solely on theoretical proton release.
- Hydrogen chloride emitted to air is insignificantly contributing to mid-point TA indicator results which are based solely on theoretical proton release.
- Carbon dioxide emitted to air is insignificantly contributing to mid-point TA indicator results which are based on proton release and acid strength.
- Hydrogen chloride emitted to air is the main contributor to mid-point TA indicator results which are based on proton release and acid strength.
- Adding the acid strength can improve those current TA mid-point indicators which are based on proton release.

2. MATERIALS AND METHODOLOGY

In this section it is explained which methods are used to obtain the results shown in section 3.

2.1. The Inventory of Acidifying Compounds from Steel Manufacturing

Solely based on Renzulli et al. [15] the following Tables 1-5 are derived. However, all input resources, emissions to water and soil, as well as and waste in

Table 1: Inventory (A) and (B) of Acidifying Compounds from Coke Production

| Output Products       | Allocation |
|-----------------------|------------|
| Tar                   | 13576      |
| Ammonium Sulphide     | 5797       |
| Purified coke gas     | 107002     |
| Coke+coke dust        | 439583     |
| **Emissions to air**  |            |
| Carbon dioxide        | 310133     |
| Carbon monoxide       | 20         |
| Nitrogen dioxide      | 634        |
| Sulfur dioxide        | 818        |
| Hydrogen cyanide      | 1          |

Table 1 shows the outputs from the coke ovens for the production of coke necessary for the production of one million tonnes of Steel.

Table 2 shows the input and outputs from the sintering furnace for the production of the sintered ore necessary for the production of one million tonnes of steel.

Table 2: Inventory (A) and (B) of Acidifying Compounds from Sinter Manufacturing

| Output Products       | Allocation |
|-----------------------|------------|
| Sinter                | 1162792    |
| **Input Materials/fuels** |          |
| Coke+coke dust        | 55262      |
| **Emissions to air**  |            |
| Carbon dioxide        | 245724     |
| Carbon monoxide       | 344        |
| Nitrogen dioxide      | 1040       |
| Sulfur dioxide        | 1617       |
| Zinc                  | 2          |
| Hydrogen chloride     | 1          |
| Hydrogen fluoride     | 54         |

Table 3 shows the outputs from the blast furnace for the production the pig iron required for the production of one million tonnes of steel.

Table 3: Inventory (A) and (B) of Acidifying Compounds from Pig iron Manufacturing

| Output Products       | Allocation |
|-----------------------|------------|
| Pig iron              | 991085     |
| Electricity (turbo expanded) | 18529     |
| **Input Materials/fuels** |          |
| BF slag               | 339444     |
| Purified BF gas       | 1463753    |
| **Emissions to air**  |            |
| Carbon dioxide        | 551845     |
| Carbon monoxide       | 32         |
| Nitrogen dioxide      | 599        |
| Sulfur dioxide        | 1320       |
Table 4 shows output from the Blast Oxygen Furnace for the production of one million tonnes of steel.

**Table 4: Inventory (\(\alpha\)) and (\(\beta\)) of Acidifying Compounds from Solid Steel Slabs Manufacturing**

| Output Products          | Allocation |
|-------------------------|------------|
| Solid steel             | 1000000 tonnes 100 |
|                         |            |

**Emissions to air**

| Substance                         | Unit | Total |
|-----------------------------------|------|-------|
| Carbon dioxide                    | tonnes | 50873 |
| Carbon monoxide                   | tonnes | 80 |
| Hydrogen fluoride                 | tonnes | 1 |

Table 5 shows the inventory result (\(\varphi\)) when Tables 1 to 4 are linked to produce (\(\gamma\)) one million tonnes of solid steel slabs.

- Only direct emissions are included in the analysis, i.e. one ton hydrogen chloride emitted to air from the sintering furnace.
- No secondary life cycle inventory databases are used to estimate the emissions from input of raw materials and electricity.
- No allocations are done of the environmental loadings between the outputs from the coke oven and the blast furnace in Tables 1 and 3, respectively. That is 100% of the environmental loadings are allocated to “coke+coke dust” and Pig iron, respectively.

**Table 5: Inventory Result (\(\varphi\)) Summary for (\(\gamma\)) one Million Tonnes solid Steel Slabs Manufacturing Output**

| Substance (Acidifying Compound, C), Emission to air (\(\varphi\)) | Compartment | Unit | Total |
|-----------------------------------------------------------------|-------------|------|-------|
| Carbon dioxide                                                  | Air         | tonnes | 887430 |
| Carbon monoxide                                                 | Air         | tonnes | 458   |
| Hydrogen chloride                                               | Air         | tonnes | 1     |
| Hydrogen cyanide                                                | Air         | tonnes | 0.125 |
| Hydrogen fluoride                                               | Air         | tonnes | 55    |
| Nitrogen dioxide                                                | Air         | tonnes | 1718  |
| Sulfur dioxide                                                  | Air         | tonnes | 3039  |
| **Output (\(\gamma\))**                                         |             |       | 1000000 |

These assumptions mainly explain why the \(I_j\) results in Table 2 in [15] are much different than in the present

**Table 6: Acids formed, Protons formed, Molar Masses, Acidity Constants of Included Acidifying Compounds**

| Acidifying compound (C) | Acid formed (D) via hydrolysis or oxidation | Protons formed | Molar mass of C (g/mole) | mmol protons/g C, \(k_{i(j)}\) | Acidity constants (K_a of D) | \([mmol protons/g C] \times [K_a of D] \times k_{i(j)}\) (new characterization factors) |
|-------------------------|---------------------------------------------|----------------|--------------------------|-------------------------------|-----------------------------|----------------------------------------------------------------------------------|
| Carbon dioxide          | \(\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3\) | 2              | 44                       | 45.45                         | 4.40\times10^{-7}            | 2.00\times10^{-5}                                                               |
| Hydrogen chloride       | \(\text{HCl} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{Cl}^-\) | 1              | 36.46                    | 27.43                         | 1.30\times10^{-6}            | 3.57\times10^{-7}                                                               |
| Hydrogen cyanide        | \(2 \text{HCN} + 6 \text{H}_2\text{O} \rightarrow 2 \text{CH}_4 + 2 \text{NH}_3 + 3 \text{O}_2\) | 1              | 27.02                    | 37.01                         | 2.4\times10^{-1}             | 8.88\times10^{-3}                                                               |
| Hydrogen fluoride       | \(\text{HF} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{F}^-\) | 1              | 20                       | 50.00                         | 6.60\times10^{-5}            | 3.30\times10^{-2}                                                               |
| Nitrogen dioxide        | \(3 \text{NO}_2 + \text{H}_2\text{O} \rightarrow 2 \text{HNO}_3 + \text{NO}\) | 1              | 46.055                   | 21.71                         | 2.4\times10^{-1}             | 5.21\times10^{-3}                                                               |
| Sulfur dioxide          | \(\text{SO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_3\) or \(2\text{SO}_2 + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{H}_2\text{SO}_4\) | 2              | 64.06                    | 31.22                         | 1.3\times10^{-2} (H_2SO_3) and 4.06\times10^{-1} (H_2SO_3) or 3.12\times10^{-2} (H_2SO_4) | 4.06\times10^{-1} (H_2SO_3) or 3.12\times10^{-2} (H_2SO_4) |
article, e.g. Acidification $1.34 \times 10^7$ mol protons in [15] and here the comparable $1.35 \times 10^6$ (Table 8 column 2).

2.2 Rationale for Proton Equivalents/Acidity Constant Method

Table 6 shows the major assumptions for the mid-point TA parameters used in the present research.

Table 7: pKa of Acids Formed

| Acidiﬁying compound (C) | Acid formed (D) via hydrolysis or oxidation | Acidity constants (pK_a) of D | [mmol protons/g C] × [pK_a of D], k_i(j) |
|-------------------------|------------------------------------------|-----------------------------|---------------------------------|
| Carbon dioxide          | H_2CO_3                                  | 6.35                        | 289                             |
| Hydrogen chloride       | H_2O^+ + Cl^-                            | -6.11                       | -167                            |
| Hydrogen cyanide        | HNO_3                                   | -1.38                       | -51                             |
| Hydrogen fluoride       | H_2O^+ + F^-                            | 3.18                        | 159                             |
| Nitrogen dioxide        | HNO_2                                  | -1.38                       | -30                             |
| Sulfur dioxide          | H_2SO_3                                 | 1.88                        | 59                              |
| Sulfur dioxide          | H_2SO_4                                | -3                          | -93.7                           |

The acidity constant (pK_a) of H_2CO_3 might be 3.76 at 25 °C [13].

The most similar method - to the present proton equivalents method excluding carbon dioxide - is BEES is a software tool developed by the National Institute of Standards and Technology in the United States [16]. BEES characterization factors k_i(j) are often included in popular LCA software. BEES expresses column five in Table 6 as "grams of hydrogen with the same potential acidifying effect as one gram of inventory flow".

3. RESULTS

Here follows a concise and precise description of the results. Tables 8 and 9 show a summary of the different mid-point TA indicators when (Tables 6 and 7) values are multiplied with the inventory result (Table 5).

Table 8 (columns 2 and 3) shows the awkward conclusion that hydrogen fluoride is more contributing to mid-point TA than hydrogen chloride. It also shows (columns 3 and 5) that if carbon dioxide is treated as hydrogen fluoride, it will dominate the mid-point TA results for steel manufacturing. The proposed ideal method (K_a normalization in column 4) solves the problems in a logical way. In the discussion it will be further elaborated what is the meaning of the results.

Tables 8 and 9 show that for the proton equivalents method excluding carbon dioxide (column 2) the trend is very similar to existing mid-point TA indicator results in which sulfur dioxide and nitrogen dioxide – with few exceptions – always dominate regardless of whether proton equivalents or sulfur dioxide equivalents is used.

Table 8: Absolute Results per f_i for new Impact Assessment Methods for Terrestrial Acidification Applied to Solid Steel Manufacturing

| Acidifying compound (C) | The proton equivalents method excluding carbon dioxide, mmol proton equivalents | The proton equivalents method including carbon dioxide, mmol proton equivalents | The proton equivalents/acidity constant method (K_a) including carbon dioxide, mmol proton equivalents | The proton equivalents/acidity constant method (pK_a) including carbon dioxide, mmol proton equivalents |
|-------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Carbon dioxide          | 0                                                                               | 4.03×10^{13}                                                                | 1.77×10^7                                                                       | 2.56×10^{14}                                                                   |
| Hydrogen chloride       | 2.74×10^7                                                                     | 4.65×10^7                                                                  | 3.57×10^{13}                                                                | -5.14×10^{10}                                                                  |
| Hydrogen cyanide        | 4.65×10^6                                                                     | 4.65×10^6                                                                  | 1.12×10^0                                                                   | -1.68×10^0                                                                   |
| Hydrogen fluoride       | 2.75×10^9                                                                     | 2.75×10^9                                                                  | 1.82×10^8                                                                   | -6.42×10^8                                                                   |
| Nitrogen dioxide        | 3.73×10^{10}                                                                  | 3.73×10^{10}                                                                | 8.95×10^11                                                                | 8.59×10^3                                                                   |
| Sulfur dioxide (H_2SO_3) | 9.49×10^{10}                                                                  | 9.49×10^{10}                                                                | 1.23×10^9                                                                   | 1.79×10^{11}                                                                  |
| Sulfur dioxide (H_2SO_4) | 9.49×10^{10}                                                                  | 9.49×10^{10}                                                                | 9.49×10^13                                                                | -2.85×10^{11}                                                                  |
| TOTAL (with (H_2SO_3))  | 1.35×10^{11}                                                                  | 4.05×10^{13}                                                                | 3.66×10^{13}                                                                | 2.57×10^{14}                                                                  |
| TOTAL (with (H_2SO_4))  | 1.35×10^{11}                                                                  | 4.05×10^{13}                                                                | 1.31×10^{14}                                                                | 2.56×10^{14}                                                                  |
DISCUSSION

One of the most striking examples which shows the unrealistic rating of acidifying substances - in every current mid-point TA method in LCMPNA - is hydrogen fluoride (whenever included such as in BEES and TRACI methodologies). As shown in Table 6, 50 mmol protons are released per gram hydrogen fluoride released into soils, making hydrogen fluoride the strongest acidifying compound of those released in the steel manufacturing processes studied [15] in the present research. The effect of hydrogen fluoride – 55 tonnes - also explains why the present baseline result (Table 8 column 2) is higher than Table 2 in [15] despite that the scope is much smaller than analyzed by Renzulli et al. [15]. Evidently, the hydrogen fluoride anion is very weak compared to e.g. the hydrogen chloride anion, nonetheless this is neglected in current mid-point TA methods.

The hydrogen carbonate anion is also very weak which logically will make carbon dioxide an insignificant contributor to mid-point TA. End-point TA is obviously totally different and experiments - as well as measurements - have to be conducted to reveal the real potential [13]. Mid-point TA is just a relative scoring which is used nonchalantly by LCA practitioners.

Using $K_a$ - which is unit less - as weighting factor for mid-point TA $K_{ij}$ gives a relative scale of positive numbers.

Using $pK_a$ numbers ($pK_a = -\log(K_a)$) - instead of $K_a$ - would render negative $pK_a$ numbers for $K_a>0$, such as -6.11 for hydrogen chloride, and positive $pK_a$ numbers for $K_a<0$, such as 6.35 for dihydrogen carbonate (Table 7). The logarithmization gives numerical values (mmol protons per gram acidifying compound released) close to current midpoint TA proton based methods. However, $pK_a$ based methods would conclude that carbon dioxide is the only important acidifying compound in TA (Table 9). This is a similar conclusion as the one that is obtained when carbon dioxide is included in current proton release based methods.

Anyway, the present mid-point TA indicator results - which are based on theoretical proton release and acid strength - are not suitable for end-point normalization as the numbers possibly would scale acidification much higher than its actual contribution to the overall environmental cost. Apart from the situation when sulfur dioxide mainly forms $H_2SO_4$ instead of $H_2SO_3$, hydrogen chloride is greatly emphasized with the present proton equivalents/acidity constant method ($K_a$) for mid-points. The common knowledge is that hydrogen chloride is somewhat important for mid-point TA while not being at the significance of sulfur dioxide and nitrogen oxides, for most process systems.

As a sensitivity check for carbon dioxide, $K_a$ 1.73×10\(^{-4}\) (pKa 3.76) [13] is used. This leads to 7×10\(^{9}\) mmol proton equivalents for the preferred proton equivalents/acidity constant method ($K_a$) – instead of the baseline 1.77×10\(^{7}\) in Table 8. The score for carbon dioxide becomes almost six times higher than for sulfur dioxide (forming $H_2SO_3$), but still cannot change any conclusions being just 0.02% of the total score 3.66×10\(^{13}\) (Table 8). When sulfur dioxide instead forms $H_2SO_4$, the share of 7×10\(^{9}\) mmol proton equivalents for carbon dioxide will be just 0.005% of 1.32×10\(^{14}\) (Table 8).

| Acidifying compound (C) | The proton equivalents method excluding carbon dioxide, Share of total result, % | The proton equivalents method including carbon dioxide, Share of total result, % | The proton equivalents/acidity constant method ($K_a$) including carbon dioxide, Share of total result, %, with $H_2SO_3$ and $H_2SO_4$ as D for SO2 | The proton equivalents/acidity constant method ($pK_a$) including carbon dioxide, Share of total result, % |
|-------------------------|-----------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------|
| Carbon dioxide          | 0                                             | 99.7                                                            | $4.85\times10^{-5} / 1.35\times10^{-5}$                                                        | 99.9                                           |
| Hydrogen chloride       | 0.0203                                         | 6.78×10\(^5\)                                                   | 97.5 / 27.1                                                                                     | -6.54×10\(^5\)                                |
| Hydrogen cyanide        | 0.00345                                        | 1.15×10\(^5\)                                                   | 3.05×10\(^{-4}\) / 8.49×10\(^{-5}\)                                                          | -2.5×10\(^6\)                                 |
| Hydrogen fluoride       | 2.04                                           | 0.0068                                                         | 4.96×10\(^{-4}\) / 1.38×10\(^{-5}\)                                                          | 0.00341                                       |
| Nitrogen dioxide        | 27.6                                           | 0.0922                                                         | 2.45 / 0.68                                                                                     | -0.02                                         |
| Sulfur dioxide ($H_2SO_3$) | 70.3                                           | 0.235                                                          | 3.37×10\(^3\)                                                                                   | 0.0698                                        |
| Sulfur dioxide ($H_2SO_4$) | 70.3                                           | 0.235                                                          | 72.2                                                                                             | -0.111                                        |
| %                       | 100                                            | 100                                                            | 100                                                                                              | 100                                           |
Commonly overall mid-point indicators \((I_j)\) are normalized in order to arrive at a single indicator such as \(EB\). It is familiar that sulfur dioxide equivalents can be normalized.

Can \(K_{IR}\) based methods for mid-point TA interplay with 'distance to target' weighting methods? If not, they would be rather limited. Lin et al. [17] proposed weighting of several different \(I_j\) including acidification expressed in sulfur dioxide equivalents for nitrogen oxides and sulfur dioxide. It would be straight-forward to apply the proposed methods to country level if used consistently.

CONCLUSIONS

The conclusions for steel manufacturing are:

- Carbon dioxide is – if included - the main contributor to mid-point TA indicator results which are based solely on theoretical proton release.

- Hydrogen chloride emitted to air is insignificantly contributing to mid-point TA indicator results which are based solely on theoretical proton release.

- Carbon dioxide emitted to air is insignificantly contributing to mid-point TA indicator results which are based on proton release and acid strength.

- Hydrogen chloride emitted to air is one of the main contributors to mid-point TA indicator results which are based on proton release and acid strength.

- The relative importance of hydrogen chloride in mid-point TA indicator results which are based on proton release and acid strength is determined by the shares of the acids \(H_2SO_3\) and \(H_2SO_4\) resulting from sulfur dioxide emissions.

- Using the acid strength with the characterization factors can improve those current mid-point TA indicators which are based on proton release.

The present research has proven that there is a precision problem with current mid-point indicators for TA which are solely based on theoretical proton release. It is concluded that hydrogen chloride emitted to air is heavily underestimated in mid-point indicators for TA for steel manufacturing.

NEXT STEPS

The relative results might look very different for other process systems that the one analyzed in the present research. For example a process system absent of hydrogen chloride emissions will have different conclusions than the present system. The next step is to clarify how acidity constant based mid-point TA indicators work with normalization of acidification such as distance to target methods. It is also worthwhile to hypothesize on whether the present mid-point TA method has any implications for end-point TA applied by environmental cost methods. Moreover, it is not evident why carbon dioxide soil acidification is not yet included in mid-point and end-point impact assessment methods.

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CONFLICTS OF INTEREST

The author declares no conflict of interest. The views of this paper is the authors own and not those of the company.

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