Modular extrapolation of crop LCA (MEXALCA): Sensitivity to varying crop yields

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ABSTRACT

A method for the geographical extrapolation of farming inputs and environmental impacts, MEXALCA, was investigated with respect to its sensitivity to variations of crop yields as evident from public statistics. A case study on wheat revealed an increase of the average global yield from 2300 (1983–1987) to 2820 kg wheat ha^{-1} (2003–2007, today's conditions) to be reflected in a 19 % average rise of the global warming potential (GWP) and the non–renewable energy demand per hectare. The corresponding impacts per kilogram wheat decreased by 10 %. Comparison of today's conditions with an average global yield of 2580 kg ha^{-1} (1993–1997) leads to 11 % (GWP) or 9 % (non–renewable energy demand) higher impacts per hectare, while the generic impacts per kilogram remain at about the same average value. The analysis revealed a strong dependency of the extrapolated inputs or impacts on the yields given for the original country.

Keywords: geographical extrapolation, variability, life cycle inventory, crop LCA, wheat

1. Introduction

Life Cycle Assessments (LCAs) are increasingly used in the food sector to estimate the environmental impacts of agricultural and processed products. However, data on such diverse production systems are seldom available and it is too time and cost intensive to calculate detailed LCAs for a multitude of products and ingredients originating from all over the world. In order to overcome this problem, several approaches are currently applied, e.g. the use of proxy data and generalisations (Muñoz *et al.*, 2010) or simplified LCAs that do not consider all processes involved (Kuan *et al.*, 2007, Zah *et al.*, 2009).

This study investigates a third approach, which is the geographical extrapolation method proposed by Roches *et al.* (2010), aiming at a simplified assessment for agricultural and horticultural crops for all producing countries worldwide, while still considering all relevant processes. MEXALCA (Modular EXtraplolation of Agricultural Life Cycle Assessment) is based on the assumption that the environmental profile of agricultural systems can be described by nine key farming operations (Nemecek *et al.*, 2005, Roches *et al.*, 2010) named modules. These are basic cropping operations, tillage machinery use, variable machinery, nitrogen, phosphorus and potassium fertiliser use, pesticide use, irrigation and drying.

A detailed Life Cycle Inventory (LCI) for a crop in a country (original country) is extrapolated to another (target) country by scaling the inputs induced by each of the modules. For scaling, estimators depending on the ratio of the yields and the farming intensities (agricultural indices) in the target and original countries are defined (see section 2). Both crop yields and farming intensities are country specific, however the latter are not crop specific but represent the prevailing economic situation or traditions specific to a certain country. Both factors are derived from FAO statistics (FAO, 2010) and EarthTrends (WRI, 2009). A list of the agricultural indices used is given in Roches *et al.* (2010). Based on the extrapolated LCIs the Life Cycle Impact Assessment (LCIA) of the crop in the target countries is

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derived. The same characterization factors are applied to all countries. As from now the extrapolation results are referred to as generic data.

A first validation of the generic LCIA results showed MEXALCA to perform well for the impact categories global warming potential (GWP), non–renewable energy demand, and photochemical ozone formation (Roches *et al.*, 2010). Data generated with MEXALCA are not intended to replace LCIA studies based on detailed input data sets referring to a specific crop production in a certain country; rather, they are meant to inform strategic decision making, identify hot spots of environmental impacts during the crop production stage, and help to understand the geographical variability of production systems on large spatial scales.

This paper addresses the sensitivity of the MEXALCA model to the variation in crop yields over the last three decades that is evident from FAO statistics (FAO, 2010). Crop yields reflect the technological and economic development of a country. At the same time, they also depend on political regulations or the occurrence of natural disasters. In a case study on wheat production up to the farm gate the effects of changing yields on the average generic inputs and impacts for two functional units, per hectare and per kilogram of wheat, are investigated. The extrapolation is based on the LCI of wheat at farm in Switzerland (Roches *et al.*, 2010).

2. Calculation of the generic inputs and impacts using MEXALCA

In order to extrapolate the original country inputs and to derive the corresponding impacts for all other wheat producing countries, estimators are defined for each of the nine modules (Roches *et al.*, 2010). The yield ratio, i.e. the yield in the target country divided by the yield in the original country, explicitly occurs in the estimators for the modules variable machinery use, nitrogen, phosphorus and potassium fertilizer use and pesticide use:

$$\hat{X}_t^c = X_o^c \cdot \frac{Y_t^c}{Y_o^c} \cdot \sqrt{\frac{ind_t^X}{ind_o^X}}. \qquad (1)$$

In addition, the yield ratio is used in the estimator for the module drying:

$$\hat{X}_t^c = X_o^c \cdot \frac{Y_t^c}{Y_o^c} \cdot \frac{ind_t^X}{ind_o^X}. \qquad (2)$$

$\hat{X}_t^c$ or- X_0^c are the amounts of farming input in the target (subscript *t*) and original (subscript *o*) country, respectively for production of crop *c* (intensity index for variable machinery use, kg N ha^{-1}, kg P_2O_5 ha^{-1}, kg K_2O ha^{-1}, kg active ingredient ha^{-1}). Y_t^c and Y_o^c are the yields in the target and original countries (kg raw product ha^{-1}), and ind_t^X and ind_o^X are the agricultural indices in the target and original countries, respectively, representing the intensity of input use (Roches *et al.*, 2010).

The estimators for basic cropping operations, tillage machinery use and water use do not include the yield ratio.

3. Variation of yields

3.1. Input scenarios and statistical measure

In order to study the sensitivity of the generic inputs and impacts to changing yields, 5–year averages are calculated using country specific wheat yields (FAO, 2010) and three different scenarios as an input to the MEXALCA model: 1983–1987 (scenario 1), 1993–1997 (scenario 2) and 2003–2007 (reference scenario reflecting today's conditions). Globally, average wheat yields increased during these three time intervals from 2300 kg ha^{-1} (scenario 1) to 2580 kg ha^{-1} (scenario 2) and 2820 kg ha^{-1} for the reference scenario. The reference scenario is indicated with a subscript *ref*, while the other intervals are marked with a subscript *int*.

Weighted averages of the generic farming inputs and environmental impacts with respect to the different yield scenarios are used as a measure for comparison. The contribution of a country to the total world production (FAO, 2010) during the time intervals mentioned above is applied as a weight. In Figures 1 and 2, farming inputs and environmental impacts are depicted with respect to the cumulated world production (in %). This is the summation of each country's contribution to the world production of wheat, while the values are sorted in ascending order on the y–axis, i.e. the generic farming inputs and environmental impacts.

3.2. Generic farming inputs per hectare

Based on the assumption that the farming inputs per hectare $\hat{X}^{c}_{t,\text{int}}\Big|_{\text{ha}}$ are linearly related to the yield ratio (see equations 1 and 2), the application of a different yield scenario leads to the following expression for the $\hat{X}^{c}_{t,\text{int}}\Big|_{\text{ha}}$ with respect to the reference $\hat{X}^{c}_{t,ref}\Big|_{\text{ha}}$:

$$\hat{X}^{c}_{t,\text{int}}\Big|_{\text{ha}} = \hat{X}^{c}_{t,ref}\Big|_{\text{ha}} \cdot \left(\frac{Y^{c}_{t}}{Y^{c}_{o}}\right)_{\text{int}} \Bigg/ \left(\frac{Y^{c}_{t}}{Y^{c}_{o}}\right)_{ref} . \tag{3}$$

Thus, for a yield ratio $\left(Y^{c}_{t}/Y^{c}_{o}\right)_{\text{int}}$ that is larger (or smaller) than the reference yield ratio $\left(Y^{c}_{t}/Y^{c}_{o}\right)_{ref}$, higher (or lower) generic farming inputs per hectare will result.

Farming inputs per hectare wheat with respect to the cumulated world production (in %) are exemplarily shown for the amount of nitrogen (N) fertilizer input (Fig. 1a) and drying input (Fig. 1b, expressed as the amount of water extracted, Roches *et al.*, 2010). Each step represents the generic farming input of a country based on the different yield scenarios. In agreement with the temporally increasing mean wheat yields (section 3.1) and as expected from equation 3, farming inputs per hectare resulting for scenarios 1 and 2 (blue and green lines) are generally lower than the reference scenario (red lines) representing today's conditions.

3.3. Generic farming inputs per kilogram of product

The generic farming inputs per kilogram of product are calculated from those per hectare by dividing by the yields in the target country $Y^{c}_{t,\text{int}}$, i.e.

$$\hat{X}^{c}_{t,\text{int}}\Big|_{\text{kg}} = \frac{\hat{X}^{c}_{t,\text{int}}\Big|_{\text{ha}}}{Y^{c}_{t,\text{int}}} = \frac{\hat{X}^{c}_{t,ref}\Big|_{\text{ha}}}{Y^{c}_{t,ref}} \cdot \frac{Y^{c}_{o,ref}}{Y^{c}_{o,\text{int}}} = \hat{X}^{c}_{t,ref}\Big|_{\text{kg}} \cdot \frac{Y^{c}_{o,ref}}{Y^{c}_{o,\text{int}}} . \tag{4}$$

Thus, the generic inputs per kilogram of product solely depend on the yields given for the original country. For a scenario with a yield input in the original country ($Y^{c}_{o,\text{int}}$) larger (smaller) than the reference scenario ($Y^{c}_{o,ref}$), generic farming inputs per kilogram $\hat{X}^{c}_{t,\text{int}}\Big|_{\text{kg}}$ turn out to be lower (higher) than the reference value.

The farming inputs per kilogram of wheat are shown in Figures 1c (N–fertilizer input) and d (input from drying). The 5–year averaged wheat yields in the original country (Switzer-

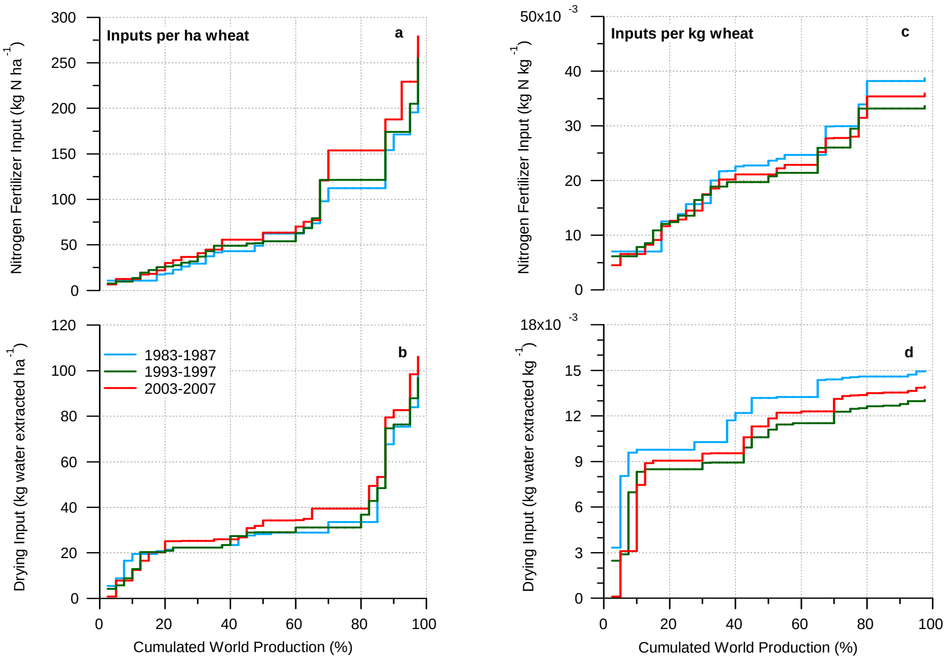

Figure 1: Generic nitrogen fertilizer and drying inputs per hectare (a, b) and per kilogram wheat (c, d) with respect to the cumulated world production as derived with MEXALCA, using Switzerland as the original country. The scenarios assume different yields extracted from FAO (2010) as an input to MEXALCA. Red lines represent results for the reference scenario (yield input averaged over the time period 2003–2007) and blue and green lines for scenarios 1 and 2 where average yields for the time intervals 1983–1987 and 1993–1997 were used, respectively.

land, FAO, 2010) vary between 5350 kg ha^{-1} (scenario 1), 6160 kg ha^{-1} (scenario 2) and 5770 kg ha^{-1} (reference scenario, $Y^c_{o,ref}$). Thus, when applying scenario 1, the factor $Y^c_{o,ref} \big/ Y^c_{o,\text{int}}$ (see equation 4) is larger than 1 and therefore, the extrapolated inputs per kilogram wheat (blue lines in Figures 1c and d) are higher than those derived from the reference input (red lines). Using scenario 2 as an input for the extrapolation, the opposite result is obtained as the yield ratio $Y^c_{o,ref} \big/ Y^c_{o,\text{int}}$ is smaller than 1: The $\hat{X}^c_{t,\text{int}}\Big|_{\text{kg}}$ (green lines) are lower with respect to the reference scenario (red lines in Figures 1c and d).

3.4 Generic environmental impacts per hectare and per kilogram wheat

Applying the same characterization factors for all countries worldwide, each of the generic environmental impacts per hectare can be calculated as the sum of the products of the generic farming inputs per hectare and module and the corresponding impacts per unit of farming input as derived for the original country (Roches *et al.*, 2010). Accordingly, the generic environmental impacts per kilogram of product are obtained by dividing those per hectare by the yield in the target countries.

Figures 2a and b show the generic global warming potential (GWP 100 a, kg CO_2-eq ha^{-1}) and the non–renewable energy demand (MJ-eq ha^{-1}) with respect to the cumulated world

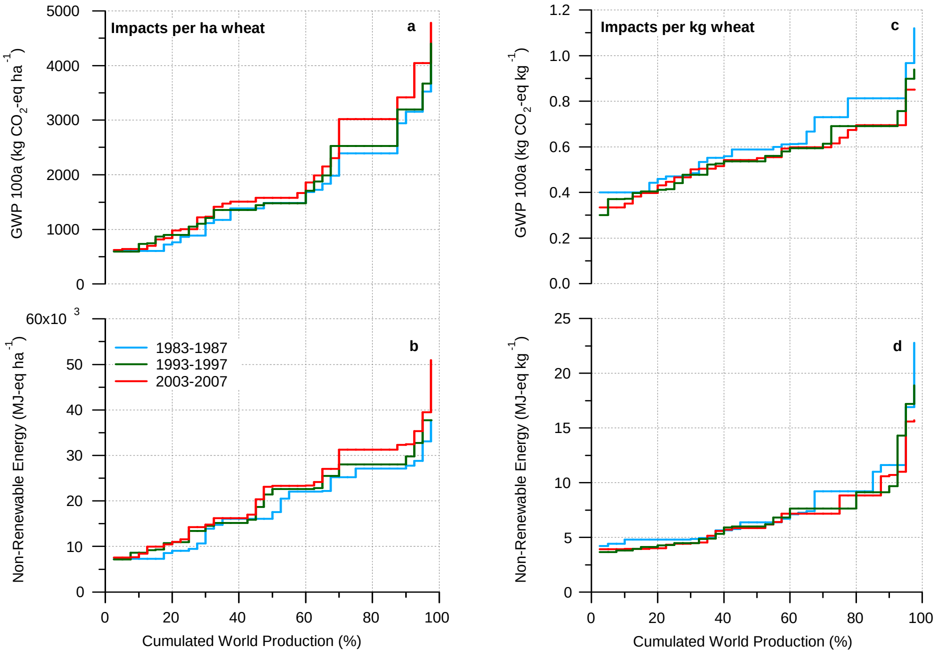

Figure 2: Generic global warming potential (100a) in CO_2–equivalents per hectare (a) and per kilogram of wheat (c) and generic non–renewable energy demand in MJ–equivalents per hectare (b) and per kilogram of wheat (d). Scenarios representing different yield inputs are coloured in the same way as in Figure 1.

production (%). Yield scenario 1 (1983–1987, blue lines) results in the smallest generic inputs per hectare, where weighted averages for both impacts are 19 % lower than for the reference scenario (red lines). Generic impacts per hectare derived from using scenario 2 (1993–1997, green lines) are calculated to be 11 % (GWP) or 9 % (non–renewable energy demand) lower on average than the reference scenario. Both findings are in agreement with the behaviour of the generic inputs per hectare (see Figure 1).

The generic impacts per kilogram of wheat are shown in Figures 2c and d. As described in section 3.2, inputs per kilogram of wheat are largest when driving the model with scenario 1 (Figures 1c and d). Accordingly, the corresponding average impacts per kilogram turn out to be 10 % higher (blue lines) than the reference (red lines) for both GWP and non–renewable energy demand. The generic impacts calculated from driving the model with scenario 2, however, are similar to those obtained from the reference input: weighted averages are only 2 % (GWP) or 4 % (non–renewable energy demand) higher than those of the latter even if the corresponding inputs per kilogram are smaller on average than the reference (Figures 1c and d).

In order to interpret this result it has to be recalled that only some of the key farming inputs (see section 2) are scaled with the yield ratio and others are not. In fact, following scenario 2, generic impacts per kilogram would be 4 % lower for both GWP and non–renewable energy demand if only the yield dependent key farming inputs were taken into account. Furthermore, the generic inputs per kilogram depend on the inverse yield as determined for the original country (Switzerland, see section 3.3) only. Thus, the higher this yield (6160 kg ha^{-1} for scenario 2 in contrast to 5770 kg ha^{-1} for the reference scenario), the lower the contribution of the yield dependent modules to the generic impact per kilogram.

4. Conclusions and outlook

The sensitivity of MEXALCA to variations of crop yields was investigated in a case study for the global production of wheat. The generic impacts per hectare for the categories GWP and non–renewable energy demand were 19 % lower on average than the reference (2003–2007: representing the highest yields) when applying scenario 1 (1983–1987: lowest yields) and 11 % and 9 % for GWP and non–renewable energy demand, respectively, lower when using scenario 2 (1993–1997). This is due to the linear dependency of the inputs and with it, the impacts per hectare on the yield ratio. Driving the model with scenario 1, generic impacts per kilogram are 10 % higher for both impacts (GWP and non–renewable energy demand), while impacts per kilogram of product show minor changes only when scenario 2 is used as an input.

This has two reasons: First, the generic inputs and impacts per kilogram of product are scaled using the inverse of the average yield for the original country, and wheat yields in Switzerland were lowest for the interval 1983–1987 and highest for 1993–1997 (FAO, 2010). Secondly, only some of the estimators applied during the extrapolation of the key farming inputs scale with the yield ratio, while others do not. Thus, the sensitivity of certain generic impacts to the yield also depends on the absolute value of the latter as the effect can be smoothed out by their contribution.

This has to be kept in mind when interpreting the extrapolated impacts: if crop yields in a country rise as a result of increasing farming inputs, this would imply higher environmental impacts, which might be smoothed out and thus not be reflected by the model. Furthermore, the behaviour of crop yields as observed for the original country might not represent the global trend. Thus, the extrapolation would be biased by the conditions of the original country. Accordingly, a next step in the analysis of the sensitivity of MEXALCA to the choice of the data would be the comparison of extrapolation results when using different original countries.

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