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Agricultural production and greenhouse gas emissions from world regions—The major trends over 40 years

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ABSTRACT

Since 1970, global agricultural production has more than doubled with agriculture and land-use change now responsible for ~1/4 of greenhouse gas emissions from human activities. Yet, while greenhouse gas (GHG) emissions per unit of agricultural product have been reduced at a global level, trends in world regions have been quantified less thoroughly. The KPI (Kaya-Porter Identity) is a novel framework for analysing trends in agricultural production and land-use change and related GHG emissions. We apply this to assess trends and differences in nine world regions over the period 1970–2007. We use a deconstructed analysis of emissions from the mix of multiple sources, and show how each is changing in terms of absolute emissions on a *per area* and *per produced unit* basis, and how the change of emissions from each source contributes to the change in total emissions over time. The doubling of global agricultural production has mainly been delivered by developing and transitional countries, and this has been mirrored by increased GHG emissions. The decoupling of emissions from production shows vast regional differences. Our estimates show that emissions *per unit crop* (as kg CO_2-equivalents per Giga Joule crop product), in Oceania, have been reduced by 94% from 1093 to 69; in Central & South America by 57% from 849 to 362; in sub-Saharan Africa by 27% from 421 to 309, and in Europe by 56% from 86 to 38. Emissions *per unit livestock* (as kg CO_2-eq. GJ^{-1} livestock product) have reduced; in sub-Saharan Africa by 24% from 6001 to 4580; in Central & South America by 61% from 3742 to 1448; in Central & Eastern Asia by 82% from 3,205 to 591, and; in North America by 28% from 878 to 632. In general, intensive and industrialised systems show the lowest emissions per unit of agricultural production.

1. Introduction

Since 1970, the human population has grown from 3.7 to more than 7 billion (UN, 2014) and higher consumption, accompanied by a shift towards more animal-based products in the diet, means that agricultural production has more than doubled (FAOSTAT, 2014). Agricultural production and land-use change (LUC) are currently responsible for ~1/4 of total greenhouse gas (GHG) emissions from human activities (Smith et al., 2014). However, it has recently been illustrated that global agriculture has been getting more efficient in terms of GHG emissions. While production has been growing fast, emissions have been increasingly decoupled from production. In 2007, the global average carbon footprint *per produced unit* crop and livestock was 39% and 44% lower than in 1970, respectively (Bennetzen et al., 2015). But these global trends tell us little about the trajectory in different world regions. GHG emissions from agriculture are most frequently reported on a *per area* basis, which tends to favour low-input system as the most environmentally benign (Gregory et al., 2002). But, for global environmental issues, such as GHG emissions, this makes little sense, since these do not affect the local area but the global climate. If one instead expresses GHG emissions *per unit of product* (i.e. emissions intensity), lower GHG emissions per area are not better than higher GHG emissions per area, if the production is also proportionately lower. Many authors argue that intensification and GHG emissions are closely linked (van Beek et al., 2010), but reality is more nuanced.

When agricultural emissions are analysed, only rarely is the complete portfolio of emissions sources included; LUC is often neglected (Bellarby et al., 2013) although up to 90% of emissions from LUC are due to agricultural activities; be it crop production, pasture or shifting cultivation (Houghton, 2012; Gibbs et al., 2010). One of the major trade-offs, on the subject of GHG emissions and sustainable agriculture in general, is whether to increase

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production by expansion of cultivated area *versus* obtaining higher yields on areas that are already cultivated (Phalan et al., 2011a; Phalan et al., 2011b; Godfray, 2011; Pretty et al., 2010; Green et al., 2005). This makes it highly relevant to include LUC in the analysis since higher agricultural yields on already cultivated areas will lead to fewer emissions from LUC (Tilman et al., 2011; West et al., 2010). Furthermore, despite an increasing dependency on external energy inputs, energy-based emissions are most often totally neglected. In the UNFCCC system, energy-use in agriculture is accounted for in the transport-, energy- and buildings-sectors (Smith et al., 2008; Schneider & Smith, 2009). Yet, if we wish to analyse how agricultural production is contributing to climate change, or maybe mitigating climate change, we need to include all energy-uses; including those from fertilizer manufacture and transportation and indirect uses for farm infrastructure.

By deploying the KPI (Kaya-Porter Identity) (Bennetzen et al., 2015; Bennetzen et al., 2012), based on the concept of the well-known Kaya identity (e.g. Raupach et al., 2007), we estimate and analyse past trends in agricultural production and LUC and related GHG emissions for nine world regions in the years 1970–2007. The KPI provides a new metric for emissions control, monitoring and analysis and allows us to identify where things are going well and not so well, to design effective abatement strategies for the most important components of land based GHG emissions. We deconstruct emissions from the mix of multiple sources of GHGs into attributable elements. This enables analyses of, not only the absolute emissions but, a combined analysis of emissions *per unit area* and emissions *per unit of production*. It also allows an assessment of how the change of emissions from each source contributes to the change in total emissions over time. Energy use and energy-based emissions are also included, enabling an analysis of energy efficiency and carbon intensity of the energy and, by including all emission sources, the total carbon footprint of agriculture.

2. Materials and methods

Using an identity approach, we estimate and analyse past GHG emissions from regional agricultural production and LUC. An identity is a mathematical construction by which the entity – the GHG emissions – can be deconstructed into elements, which affect the entity of emissions. The KPI is multi-scale and can be used to analyse any discrete agricultural system from field to farm and at national (Bennetzen et al., 2012) to global level (Bennetzen et al., 2015). In this study we apply the KPI at world regional level. We apply two identities – KPI-C for crop production (Eq. (1)) and KPI-L for livestock production (Eq. (2)) – which, when combined, estimate emissions from the total agricultural sector. Each identity and all elements are estimated for each year in the period from 1970–2007 for nine regions defined as Central- and Eastern Asia (CEA), Central- and South America (CSA), Eastern Europe and Russia (EER), Europe (EUR), Middle East and Northern Africa (MENA), North America (NA), Oceania (OCE), South- and South East Asia (SSEA) and Sub-Saharan Africa (SSA).

Emission sources included are enteric fermentation by livestock (CH_4), manure storage and handling (CH_4 and N_2O), application of N from fertilizer and manure (N2O), rice cultivation (CH_4), direct on-farm energy use (CO_2), indirect energy use for manufacture of fertilizers, machinery and buildings (CO_2), LUC (CO_2) and from production of used fodder (CO_2, N_2O and CH_4). The CO_2 net flux over continuously cultivated fields is argued to be largely in balance (Smith et al., 2014; USEPA, 2013; Houghton et al., 2012) and thus assumed to be zero. All data on area and production are derived at regional level from the FAOSTAT database (FAOSTAT, 2014). Emissions are estimated as activity data multiplied by emission factors (EmFs). Emissions from enteric fermentation and manure and from soils are estimated according to the tier 1 IPCC 1996 inventory guidelines using regional default EmFs (Table S1). Data on energy use and EmFs (Table S2) are from the UN Energy Statistics Database for fossil- and electricity energy use (UN, 2011), from the International Rice Research Institute (IRRI, 2012) combined with own assumptions based on literature (Starkey, 1988; Starkey, 2011; Ramaswamy, 1987) for energy use by draught animals, and from FAOSTAT for labour power. Data on regional LUC emissions are derived directly from CDIAC (Carbon Dioxide Information Analysis Center) (Houghton, 2008); hence not our own estimates.

We use the same data sources and methods as described in Bennetzen et al. (2015), with the exception that in this study, all analysis are conducted on a regional level. Hence, for full methods see the Supplementary Materials or Bennetzen et al. (2015).

Briefly we illustrate the identities and the one variable – GHG emissions from fodder use – which differs from the method used in Bennetzen et al. (2015), by taking regional imports and exports of fodder into account.

Equation 1. KPI-C:

$$\mathrm{GHG_{crop}} \equiv \left(\frac{\mathrm{GHG_{LUC}}}{E_{c;\mathrm{out}}} + \frac{GHG_{\mathrm{soil}}}{E_{c;\mathrm{out}}} + \left(\frac{\mathrm{GHG}_{c;\mathrm{in}}}{E_{c;\mathrm{in}}} \times \frac{E_{c;\mathrm{in}}}{E_{c;\mathrm{out}}}\right)\right) \times \frac{E_{c;\mathrm{out}}}{\mathrm{DM}_{c;\mathrm{out}}} \times \frac{DM_{c;\mathrm{out}}}{\mathrm{area_{crop;all}}} \times \mathrm{area_{crop;food}} \quad (1)$$

where $\mathrm{area_{crop;food}}$ is the cropped area excluding that used for producing animal fodder, $\mathrm{area_{crop;all}}$ is the total cropped area, $\mathrm{DM_{c;out}}$ is the dry matter crop produced, $\mathrm{E_{c;out}}$ is the energy contained in harvested crops, $\mathrm{E_{c;in}}$ is the energy use, $\mathrm{GHG_{c;in}}$ is emissions from energy use, $\mathrm{GHG_{soil}}$ is CH_4, N_2O and CO_2 emissions from cultivated soils and $\mathrm{GHG_{LUC}}$ is CO_2 emissions from LUC.

The KPI for livestock production (Eq. (2)) is conceptually similar to KPI-C and they are designed to be used simultaneously. The crop-identity (Eq. (1)) includes both GHG emissions directly from crop production and those from LUC.

Equation 2: KPI-L

$$\mathrm{GHG_{livestock}} \equiv \left(\frac{\mathrm{GHG_{fodder}}}{\mathrm{E_{l;out}}} + \frac{\mathrm{GHG_{efmh}}}{E_{l;\mathrm{out}}} + \left(\frac{\mathrm{GHG_{l;in}}}{E_{l;\mathrm{in}}} \times \frac{E_{l;\mathrm{in}}}{E_{l;\mathrm{out}}}\right)\right) \times \frac{E_{l;\mathrm{out}}}{\mathrm{DM}_{l;\mathrm{out}}} \times \frac{\mathrm{DM}_{l;\mathrm{out}}}{\mathrm{area}_l} \times \mathrm{area}_l \quad (2)$$

where areal is the area used for permanent pastures and meadows and for fodder production, $\mathrm{DM_{l;out}}$ is the dry matter of eatable produced animal products, $\mathrm{E_{l;out}}$ the energy contained in these animal products, $\mathrm{E_{l;in}}$ is the energy use, $\mathrm{GHG_{l;in}}$ is emissions from energy use, $\mathrm{GHG_{efmh}}$ is CH_4 and N_2O emissions from enteric fermentation and manure handling and $\mathrm{GHG_{fodder}}$ is GHG emissions associated with production of consumed fodder. $\mathrm{GHG_{fodder}}$ is the GHG emissions associated with production of the fodder used in the region. For each region, emissions from fodder come from what is produced plus what is imported minus what is exported. The method of calculation is illustrated below for region 'j' and all other regions being '$i-x$'. The use of fodder in region 'j' is partitioned by domestically produced and imported fodder (Eq. (3)). Emissions from domestically produced fodder are estimated as fodder produced minus fodder exported multiplied by regional emissions per unit crop for that year (Eq. (4)). Emissions from imported fodder are estimated as DM import multiplied by a regional and yearly specific EmF. The EmF is estimated as the sum of emissions from fodder exported from regions '$i-x$' (regional GHG per DM crop multiplied by DM fodder exported), divided by the total amount of exported fodder from regions '$i-x$' (Eq. (5)). This ensures that emission intensities from the high-exporting regions (e.g. CSA) are weighted proportionately and vice versa. Due to limited information on the origin of