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Review

Agricultural residue production and potentials for energy and materials services

Niclas Scott Bentsen [a,*], Claus Felby [a], Bo Jellesmark Thorsen [b]

[a] University of Copenhagen, Faculty of Science, Department of Geosciences and Natural Resource Management, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark

[b] University of Copenhagen, Faculty of Science, Department of Food and Resource Economics, Rolighedsvej 25, DK-1958 Frederiksberg C, Denmark

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Agricultural residues are potentially major contributors of resources for energy and material production. We provide regional and global estimates of the amount of residues from major crops and address the sources of uncertainty in the estimation of the amount of agricultural residues produced globally. Data and methods available currently limit the use of resource estimates for energy or production planning. We develop function based multipliers to estimate the global production of agricultural residues. The multipliers are applied to the production of the, on a global scale, six most important crops: barley, maize, rice, soybean, sugar cane and wheat in 227 countries and territories of the world. We find a global production of residues from these six crops of $3.7^{+1.3}_{-1.0}$ Pg dry matter yr^{-1}. North and South America, Eastern, South-Eastern and Southern Asia and Eastern Europe each produce more than 200 Tg yr^{-1}. The theoretical energy potential from the selected crop residues is estimated to 65 EJ yr^{-1} corresponding to 15% of the global primary energy consumption or 66% of the world's energy consumption for transport. Development towards high input agriculture can increase the global residue production by ~1.3 Pg dry matter yr^{-1}.

Contents

* Corresponding author. Tel.: +45 20 20 63 18.
E-mail address: nb@ign.ku.dk (N.S. Bentsen).

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Nomenclature

Y	crop yield (kg ha^{-1} yr^{-1})
RP	agricultural residue production (kg yr^{-1})
RPR	residue to product ratio
HI	harvest index
RY	crop residue yield (kg ha^{-1} yr^{-1})
IY	increased crop yield (kg ha^{-1} yr^{-1})
IRY	increased crop residue yield (kg ha^{-1} yr^{-1})
LHV	lower heating value (MJ kg^{-1})
HHV	higher heating value (MJ kg^{-1})

1. Introduction

The potential of biomass resources has been subject to increasing research and debate over the recent years. International and national agreements as the Kyoto Protocol [1] and EU Directives [2,3]; and policies as the European 20:20:20 Plan [4] and the US Recovery and Reinvestment Act [5] have put substantial pressure on politics promoting and sustaining the use of alternative energy carriers. The steep increase in oil prices in 2008 [6] further turned commercial attention towards alternative energy resources. The United Nations estimates that the current population of 6.9 Billion will increase to 9.1 Billion by 2050 [7], with increased demand for food, materials and energy as a consequence. The International Energy Agency estimates that energy consumption will increase with an expected 1.6% annual rate from 2005 to 2030 [8].

Biomass offers several options for displacing fossil resources [9–11]. An important question for policy and planning purposes is what amount of biomass resources is available. Several estimates of agricultural crop residue production or potential have been published in peer reviewed journals over the last 20 years providing different results. Estimates on global scale vary from 10 to 69 EJ yr^{-1} in 2050 [12–15], differences owing to different methodology and assumptions regarding residue production and ecological and economic availability of the resource. A common trait of many studies is the use of simple assumptions regarding residue production and ecological availability of agricultural residues. A number of studies apply scalar multipliers to crop production to estimate residue production [13,16–21], meaning that the amount of residue from a crop is assumed proportional to the total production of the crop, and not on the yield per area unit of the crop. A few apply function based multipliers [15,22,23], assuming that residue production is proportional to crop yield. The assessment regarding ecological and/or economic availability of crop residues tends to build on crude assumptions and often fixed scalar recovery rates used at national, regional or global level.

In this analysis we develop function based multipliers for estimating agricultural residue production based on crop yield. We apply the indicators on the global production of barley, maize, rice, soybean, sugar cane and wheat and estimate residue potentials for 22 geographical regions of the world. Also we estimate residue yields potentially achievable through agricultural intensification, and perform an analysis of the sensitivity of estimates.

2. Materials and methods

The assessment of agricultural production and residue potential builds on statistics from the Food and Agriculture Organization of the United Nations [24]. Harvested areas and crop yields are taken as averages over the three year period 2006–2008. The assessment covers all 227 countries and territories in the FAO database. Results are presented as aggregates into 22 geographical regions.

Six globally important crops in terms of production quantities are considered [24]; barley, maize, rice, soybean, sugar cane and wheat. Harvested area of these six crops covers 702 million ha corresponding to 50% of the world's arable land (1411 million ha) [24]. In FAO terms arable land include temporary crops (which covers the crops selected here), temporary meadows and pastures and fallow land. FAO does not provide a breakdown into these categories on a global level. Crop residues comprise straw from barley, rice, soy bean and wheat; stover from maize; and bagasse from sugar cane.

2.1. Theory/calculation

Residue production (RP) (kg yr^{-1}) for crop j in country i is calculated as:

$$\mathrm{RP}_{ij} = A_{ij} \cdot \mathrm{RY}_{ij}, \tag{1}$$

where A is harvested area and RY (kg yr^{-1}) residue yield by country and crop.

Residue yield is calculated from the residue to product ratio (RPR) for crop j. Empirical evidence suggests that RPR is not constant but proportional to yield (Y) (kg ha^{-1} yr^{-1}) [22,23,25]. Breeding in the 20th century has, specifically for cereals, increased the harvest index without significant changes in total biomass production [26] indicating an asymptotic development towards a theoretical limit determined by physiological constraints. This suggests an exponential relation between crop yield and residue yield, which is also shown by Scarlat et al. [23]. We assume a relation of the general form:

$$\mathrm{RPR}(Y) = ae^{bY}, \tag{2}$$

with residue yield calculated as:

$$\mathrm{RY}(Y) = Y \cdot ae^{bY}. \tag{3}$$

For $a > 0$ and $b < 0$ function (3) will, with increasing Y, decrease after a certain point and converge asymptotically toward zero. Such a development is not consistent with empirical evidence [27]. Residue yields tend to increase to a certain level with increasing crop yields and remain, in practice, constant hereafter. Building on the above assumptions we apply a piecewise continuous model for estimating residue yield as a function of crop yield for barley, maize, rice, soybean and wheat (see also Fig. 2):

$$\mathrm{RY}_{ij}(Y_{ij}) = \left\{ \begin{array}{c} Y_{ij} \cdot a_j e^{b_j Y_{ij}} \text{for } 0 \le Y_{ij} \le \frac{-1}{b_j} \\ \frac{-a_j}{b_j e} \text{ for } Y_{ij} > \frac{-1}{b_j} \end{array} \right\} \forall a > 0,\ b < 0. \tag{4}$$

Yield experiments, probably also including measurements of residue production, are carried out in many countries by national agricultural extension services. Such data are, however, not readily accessible. Consequently we estimate parameters a and b in equation (2) on the basis of tabular data published in peer reviewed papers over the last 15–20 years (Table 1). The review has been limited to literature in English and data are evaluated as representing a fraction of published data. When RPR is not provided directly, RPR is calculated from harvest indices (HI) for each crop:

$$\mathrm{RPR} = \frac{1 - \mathrm{HI}}{\mathrm{HI}} = \frac{\mathrm{RY}}{Y}. \tag{5}$$

Harvest index is a measure of a plants partitioning of aboveground biomass into crop (grain) and other biomass. It expresses the weight of the crop relative to the total aboveground biomass