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Solar energy conserved in biomass: Sustainable bioenergy use and reduction of land use change

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ABSTRACT

Climate change mitigation requires a shift from fossil energy resources to renewables, and bioenergy crops are considered one of the major potential resources. At the same time future energy supplies are expected to be sustainable, but the sustainability of energy crop production is challenged by concerns over its potential competition for arable land and disruption of food and feed markets. Protein in plant biomass is a challenge for sustainability, but also an opportunity. The challenge with protein is a disproportionately large land use foot print associated with its biosynthesis. Bioenergy exploits solar energy temporarily stored in biomass compounds such as carbohydrate, lipid, lignin, protein and organic acids. Here we review energy cost estimates for photosynthesis and growth and maintenance respiration and show – by comparing energy costs with the amount of energy stored in different plant compounds – that protein conservation could improve the sustainability of energy crop production by reducing land use impacts. The opportunity with protein in plant biomass comes from the fact that favored energy crops like switch grass, reed grass and *Miscanthus* are excellent protein producers on par with soybean and other protein-rich crops. Due to the scale of potential future bioenergy deployment we find that energy strategies involving large amounts of herbaceous energy crops will not be sustainable unless the proteins are conserved in some way.

1. Introduction

It is commonly agreed that the combat against climate change requires a fundamental change in the way energy is produced with a shift from fossil energy resources to renewables. Currently (2014) biomass contributes with 58.5 EJ to the global primary energy consumption [1] and is by far the largest renewable energy resource. Most, if not all, of the more comprehensive global energy projections predict bioenergy to play a significant and increasing role in the future energy supply. To meet the Sustainable Energy for all (SE4All) target of doubling the share of renewable energy in the global energy mix before 2030, the International Renewable Energy Agency (IRENA), estimates 108 EJ yr^{-1} of biomass to be used by 2030 [2]. The International Energy Agency (IEA) estimates in their World Energy Outlook [3] bioenergy use to increase by approximately 40% between 2011 and 2035. The Global Energy Assessment [4] stipulates significant growth in bioenergy to 80–140 EJ by 2050 rising to ~220 EJ yr^{-1} by 2100, including extensive use of agricultural residues and 2nd generation bioenergy based on lignocellulosic material. Similarly the Intergovernmental Panel on Climate Change (IPCC) in their 5th assessment report [5] outlined bioenergy use by 2100 to be up to 200 EJ yr^{-1} depending on climate ambitions and chosen policy instruments. Residue biomass from agriculture is abundantly produced on global and regional scales [6]. The IPCC Special Report on Renewable Energy assessed the technical potential of agricultural residues to 15–70 EJ yr^{-1} by 2050 [7]. More recent estimates suggest a technical potential of 13–30 EJ yr^{-1} by 2030 [2] and correspondingly 27–30 EJ yr^{-1} by 2050 [8]. Considering the many challenges in accurately estimating agricultural residue resources [9,10] it can be assumed that around 30 EJ yr^{-1} could be technically available for future energy purposes. Forest residues make up another significant bioenergy resource base [9,11] technically capable of supplying up to 35 EJ yr^{-1} [11]. Agricultural and forest residues are considered insufficient to meet the increased demand for bioenergy [12]. Consequently energy crops i.e. crops grown dedicatedly on arable or marginal land to supply energy, is considered a major resource in bioenergy projections [7,9,11,13,14].

Reports have expressed concern over the use of biomass grown on agricultural lands for energy purposes due to its potential displacement of other production (food or feed) [15] or impact on carbon reservoirs

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Table 1
Solar energy conserved in plant compounds. Solar energy input was estimated on the basis of substrate requirement for growth and maintenance respiration of plant compounds. Energy content was calculated as the higher heating value (HHV) based on the mass fraction of carbon, hydrogen, oxygen and nitrogen in the compounds.

Plant compound	Representative compound	Representative molecular formula[a]	Respiration cost (g glucose (g compound)$^{-1}$)				Energy input[d] (kJ g^{-1})
			Growth[a]	Protein turnover[b]	Solute gradient maintenance[c]	Total	
Carbohydrate	Monomer	$C_6H_{12}O_6$	1.00		0.43	1.43	261.9
	Sucrose	$C_{12}H_{22}O_{11}$	1.05		0.43	1.48	271.6
	Cellulose	$C_6H_{10}O_5$	1.11		0.43	1.54	282.3
	Hemicellulose	$C_{11}H_{18}O_9$	1.12		0.43	1.55	284.3
Lipid	Glyceryl trioleate	$C_{57}H_{101}O_6$	2.59		0.43	3.02	553.3
Lignin	Coniferyl alcohol	$C_{10}H_{12}O_3$	1.92		0.43	2.35	429.7
Protein	Zein	$C_{4.6}H_{7.0}N_{1.0}O_{1.4}S_{0.02}$	2.08	3.04	0.43	5.55	1016.8
Organic acid	Citric acid	$C_6H_8O_7$	0.70		0.43	1.13	207.7

[a] Based on McDermitt and Loomis [41].
[b] Protein mass was assumed to increase linearly over the course of 150 days. The total protein turnover cost was calculated using a mean specific protein turnover cost of 40.5 mg glucose per g protein per day [39].
[c] The cost of maintaining solute gradients has been reported to make up approximately 20% of the total respiratory costs [39]. In this analysis the respiration cost was calculated on the basis of a typical composition of Switch grass [42].
[d] Energy input was found by multiplying the total respiration cost, expressed in g glucose, by 183.2 kJ g^{-1} glucose, the theoretical minimum solar energy requirement for glucose synthesis [36].

in soil and biomass [16]. Replacing one cropping system with another incurs a direct land use change (dLUC), which may influence the state of agricultural lands in terms of soil carbon accumulation [17–21], water use [22–25], nutrient availability [21,23] or soil erosion [26–29]. Another concern relates to market-mediated effects when either cropping systems are changed or the use of crops is changed, e.g. using corn for ethanol production instead of for food or feed. Market mechanisms compensate for the changes in demand by encouraging intensified production or agriculture expanding into undeveloped lands (iLUC) [30–32] which is a serious threat to remaining forests particularly in developing countries [33]. iLUC is likely to lead to increased greenhouse gas emissions from bioenergy production [16,34], and thus offset one of the potential benefits of using bioenergy.

Bioenergy has strong potentials to ensure local supply security and to contribute to climate change mitigation [7,35]. Supplying bioenergy sustainably and in the stipulated amounts, however, requires a new perspective on intelligent use of biomass. Here we review early cost estimates for growth and maintenance respiration of plant compounds, and relate those to land requirements and land use change issues for bioenergy production, and show that energy crop production fails to meet sustainability intentions included in most renewable energy policies unless valuable proteins in the biomass somehow is conserved.

2. Material and methods

2.1. Photosynthesis

Bioenergy essentially exploits solar energy conserved in biomass and requires partial or complete decomposition of the biomass or its individual compounds to release the conserved energy. Plant matter primarily is made up of carbohydrate, lipid, lignin, protein and organic acids in various proportions. Synthesis of these individual compounds requires energy and substrate in the form of ATP, NADH and primary photosynthates. In C4 plants, such as sugarcane, corn, switchgrass or *Miscanthus*, the theoretical conversion efficiency of solar radiation to glucose is 8.5% [36]. When the enthalpy of glucose is 15.57 kJ g^{-1} [37] synthesis of 1 g of glucose requires a minimum of 183.2 kJ of absorbed solar radiation.

2.2. Growth and maintenance respiration

Respiration has been divided phenomenologically into growth respiration and maintenance respiration [38] although a three-part division has later appeared [39]. Biomass production requires input of carbohydrates to generate the energy carriers, ATP and NADH and to provide carbon skeletons for the biosynthesis of more structured plant compounds [38,40]. Growth respiration of carbohydrates provides the carbon skeletons and the reducing power required for biosynthesis as plant compounds generally are more reduced than carbohydrates [39]. Plant compounds can be characterized as biosynthetically ‘cheap’ to produce (polymeric carbohydrate and organic acids) or ‘expensive’ (lipid, lignin and protein), and the amount of growth respiration required to synthesize 1 g of different compounds varies almost four-fold (Table 1). We here used glyceryl trioleate, coniferyl alcohol, zein and citric acid as representative storage lipid, lignin monomer, cereal storage protein and common organic acid, respectively.

Maintenance respiration provides energy for repair and maintenance of biomass compounds. It is thought that a major part of the energy cost for maintenance is associated with protein turnover and the maintenance of solute gradients across cell membranes [39]. As such, maintenance and turnover of protein adds considerably to the energy cost of maintenance respiration.

3. Results and discussion

The overall theoretical efficiency of C3 and C4 plant production (photosynthesis + respiration) is 4.6% and 6.0% respectively, when estimated at 30 °C and the present atmospheric CO_2 concentration of 387 ppm [36]. This is why C4 grasses such as *Miscanthus* and sugar cane are considered to be the best energy crops. However, at lower temperatures, such as those prevalent in Northern Europe, the advantage of C4 plants is reduced [36,43]. A high-yielding C3 crop like sugar beet, where the sugar is the primary product and the biofuel in the form of waste biomass is a bonus, becomes very competitive under these conditions with a productivity almost on level with sugar cane [44].

The theoretical efficiency covers a considerable range of conversion efficiencies between individual plant compounds as reported in several studies [38,40,41,45]. McDermitt and Loomis [41] found that the energy content of biomass compounds correlates well with the amount of energy required to synthesize the compound. Their analysis did not consider energy spent on maintenance respiration (protein turnover and solute gradient maintenance). Including maintenance respiration in the analysis shows that protein differs significantly from other compounds in terms of energy return on investment (Fig. 1).