FIBRE CROPS FOR ENERGY PRODUCTION AND ENERGY SAVING

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Abstract

The photosynthesis process generates beside carbon hydrates also complex chemical compounds. The artificial synthesis of such compounds is often impossible or may require high energy input compared with their heating value. In other words, the entropy of energy crops is low compared with that of fossil fuels. This fact is usually neglected in energy analysis of bio fuels resulting in questionable political decisions concerning renewable energy. This paper demonstrates that the energy saving and the GHG mitigation potential of fibre crops may be enhanced using them first used as raw material for commercial products before processing to fuel at the end of their lifetime. For example, reed canary grass may be used for paper production and after recycling the used paper can be processed to insulation material in buildings before thermal use. Such a chain of usage trades off both, the low entropy as raw material for pulp and the heat value of the carbon hydrates. A calculation model is presented to estimate the reduction of CO_2 equivalents of the following two options: Alternative A: Production of reed canary grass + processing to fuel for heating. Alternative B: Production of reed canary grass + processing to paper + recycling of paper + processing to insulation material + installation of insulation material in buildings + recycling of insulation material + processing for heating. The results show that alternative B is outclassing alternative A. Pulp made of reed canary grass for paper and insulation material saves between ten and hundred times or more energy compared with the energy yield of burning. However, fossil fuels render a higher energy return on investment and are for the time being more competitive than both options.

Key words: Fibre crops, energy crops, GHG mitigation, reed canary grass.

Introduction

Energy crops are still considered as an important renewable energy source even though there are many doubts whether they may replace fossil fuels sustainably. The question whether the ‘cure is worse than the disease’ (Doornbosch and Steenblik, 2007) emerged, when the awareness about environmental impacts of energy crop production especially in the tropics reached public awareness (Fritsche et al., 2006; Mathews, 2007; European Environment Agency, 2007; Fargione, 2008; Searchinger et al. 2009, Young, 2009). A living crop decreases the entropy of matter by the photosynthesis process generating beside carbon hydrates also more complex chemical compounds. Therefore, many crops are used not only for food production but also as raw material for production of commodities (Smeder and Liljedahl, 1996). Energy crops do not only compete with food crops and feed crops, but also with fibre crops for industrial products. This fact is often neglected in energy analysis of energy crops. The GHG mitigation potential of fibre crops may be enhanced using them first as raw material for commodities before processing to fuel at the end of their lifetime. Such a chain of usage trades off both, the low entropy of the fibre and the heating value of the fibre.

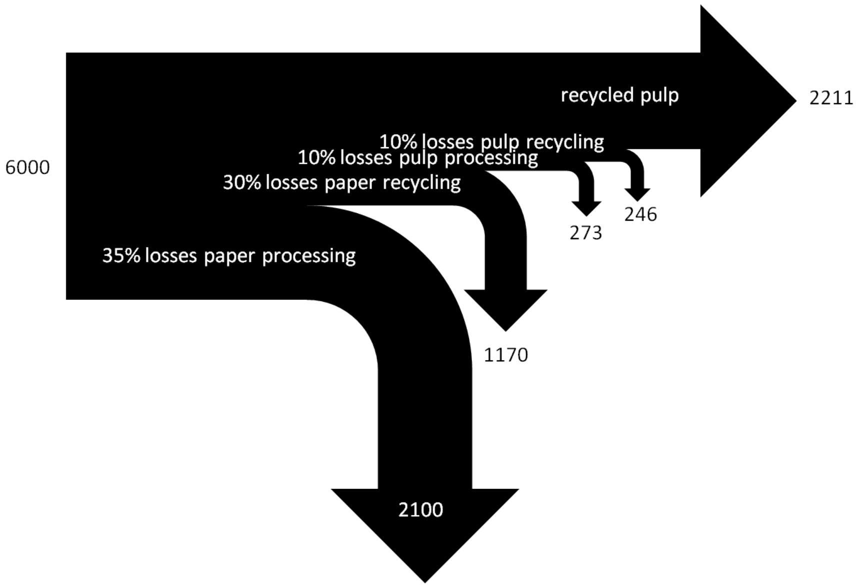
Materials and methods

The calculation model to estimate the reduction of CO_2 equivalents of fibre crops uses reed canary grass (RCG) (*phalaris arundinacea)* as an example. Alternative A includes the production and the processing of RCG to fuel for heating. Hadders and Olsson (1997), Mäkinen et al. (2006), and Lötjönen et al. (2009) describe the process of cultivating and processing and the assumptions made. The heating value h of RCG is about 17 MJ kg^{-1} and the energy gain E_h burning RCG is calculated using equation (1) where Y is the dry matter yield of RCG:

$$E_h = Y \cdot h \quad MJ\ ha^{-1}\ E_h = Y \cdot h \quad MJ\ ha^{-1} \tag{1}$$

Alternative B includes the production of RCG, the processing of RCG to paper, recycling of used paper, processing of recycled paper to pulp as insulation material, installation of pulp in buildings, recycling of pulp, and processing the residues to fuel for heating as in alternative A.

The fibre yield is processed to paper with a mean mass efficiency η_y of 65% (Finell, 2003). The process energy of paper production from birch is 38 MJ kg^{-1} and the CO_2 eq. 1.1 kg kg^{-1} (Gromke and Detzel, 2006). The credit of lower process energy of paper production from RCG compared with pulp from wood is neglected. The recycling efficiency η_p of used paper is about 70% (Finnish Forest Industries Yearbook, 2007) and the mass efficiency η_{pr} of processing used paper to pulp is estimated to 90%. The process energy of pulp production is 3.25 MJ kg^{-1} and the CO_2 emissions about 0.2 kg kg^{-1} (Rakennustieto, 2000). The heating value of the mass losses for processing may compensate the energy demand for installation of the pulp as insulation



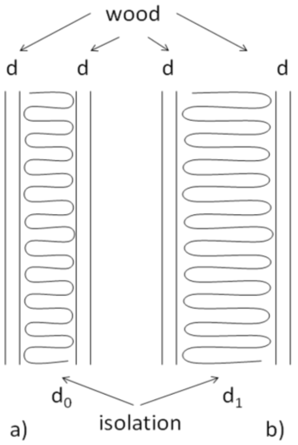
Source: yield 6000 kg ha^{-1}: estimated, 35% losses paper processing: Finell (2003), 30% losses paper recycling: Finnish Forest Industries Yearbook (2007), 10% losses pulp processing: estimated, 10% losses pulp recycling: estimated.

Figure 1. **Mass flow of alternative B. All mass figures in kg ha^{-1}**

material in buildings, recycling, and transport. Figure 1 shows the mass flow of alternative B.

To calculate the saved energy using the pulp in buildings for improvement of heat insulation, the model wall or ceiling construction described in Figure 2 is used. Figure 2a shows a simple wall element made of two d = 0.022 m thick wood walls filled with pulp insulation. The U-value of the wall insulation declines widening the insulation thickness increment $\Delta d = d_1 - d_0$ in fig 2b. Therefore, the saved energy depends on two variables, the original insulation, and the improved insulation.

The installation density ρ of the pulp is 30 kg m^{-3} and determines together with the thickness of insulation the amount of square meters of the model wall or ceiling to be insulated with the fibre yield of one hectare. The thermal conductivity of wood λ_w is 0.14 and of pulp λ_p 0.041 W K^{-1} m^{-1}. The external surface resistance R_e = 0.13 m^2 K W^{-1} and the internal surface resistance R_i = 0.04 m^2 K W^{-1} for the horizontal heat flow through walls (EN ISO 6946, 1997). The mean temperature in middle Finland (Jyväskylä) T_m is 0.87°C during the heating period of 273 days from September to May (Finnish Meteorological Institute, 2011). The room temperature T_r is +20°C. The lifetime of the insulation v is estimated to 50 years. The saved energy E_S during the lifetime of the wall is then calculated with following equations:



Source: made by the author

Figure 2. **Model wall construction, a) original insulation, b) improved insulation. d_0 = original insulation thickness, d_1 = thickness of wider insulation, d = thickness of the inner and outer wood wall**

$$E_S = (U_0 - U_1) \cdot Y \cdot \eta_y \cdot \ \eta_y \cdot \eta_r \cdot (\rho \cdot \Delta d)^{-1} \cdot (T_r - T_m) \cdot d \cdot v \cdot 0.0864 \quad MJ\ ha^{-1} \tag{2}$$

$$U_0 = \left(R_i + 2 \cdot d_w \cdot \ \lambda_w^{-1} + \ d_0 \cdot \lambda_p^{-1} + R_a\right)^{-1} \quad W\ K^{-1} m^2 \tag{3}$$

$$U_1 = \left(R_i + 2 \cdot d_w \cdot \ \lambda_w^{-1} + \ [\![(d]\!]_0 + \Delta d) \cdot \lambda_p^{-1} + R_a\right)^{-1} \quad W\ K^{-1} m^2 \tag{4}$$

At the end of the lifetime, the pulp can be used as fuel for burning assuming a recycling efficiency of 90%.

The ratio of E_s/E_h shows, how much more energy can be saved using the pulp for insulation compared with burning RCG. The heating value of pulp may be similar to that of RCG and burning this waste may additionally improve the energy balance. However, usually boron is added to the pulp as flame retardant compound, which decreases the lower heating value.

The energy return on investment (EROI) is calculated from the energy input E_{in} and output E_{out} using the following equation:

$$EROI = \frac{E_{out} \ - \ E_{in}}{E_{in}} \tag{5}$$

The CO_2 equivalent emission mitigation from the saved energy depends mainly on the substituted fuel mix. Any conversion factor for energy conversion into CO_2 equivalents may be used. It will not change the quality of the results.

Results and discussion

The energy input for RCG production is 0.078 GJ GJ^{-1} and the CO_2 eq. balance is 0.015 kg CO_2 MJ^1 (Lötjönen et al. 2009 after Mäkinen et al. 2006). Thus the *EROI* for heat production from RCG is 11.8 MJ MJ^{-1} assuming a dry matter yield of 6 Mg ha^1 corresponding to a gross energy yield of 102 GJ ha^1. However, this calculation takes into consideration only 8 GJ ha^1 for fuels and fertilisers as energy input of RCG production.

$$EROI = \frac{102\ MJ\ ha^{-1} - \ 8\ MJ\ ha^{-1}}{8\ MJ\ ha^{-1}} = 11.75\ MJ^{-MJ} \tag{6}$$

The proportion of indirect energy input reached in 1999 in Danish agriculture more than 70% (Rydberg and Haden, 2006) of the total energy input. Given ⅓ of the total indirect energy input into agricultural production is used up by crop production, indirect energy input for RCG may reach 6.2 GJ/ha. Thus, a realistic value of the *EROI* is about 6.2 MJ MJ^{-1}. The realistic net energy gain is than about 88 GJ ha^1.

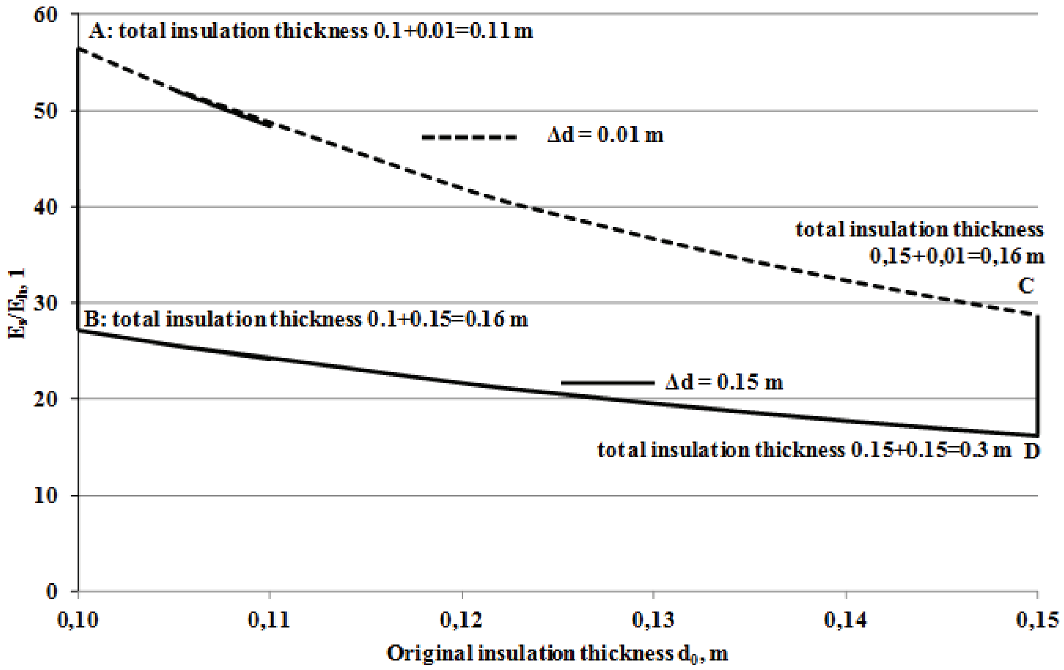
$$EROI = \frac{102\ MJ\ ha^{-1} - (8 + 6.2) MJ\ ha^{-1}}{(8 + 6.2) MJ\ ha^{-1}} = 6.18\ MJ^{-MJ} \tag{7}$$

If RCG would be used for biogas production, the energy gain may reach the half compared with burning. Although biogas may replace fossil fuels for combustion engines, the *EROI* would be too low to become a competitive alternative to fossil fuels. The *EROI* of fossil fuels ranges after Pimentel (2008) between 10 and 20.

The saved energy of alternative B is in equation (2) expressed as a function of the original insulation thickness and the insulation thickness increment Δd as parameter. The original insulation thickness d_0 may e.g. range between 0.1 and 0.15 m. Then the area enclosed by the points ABCD in Figure 3 embraces the energy saving potential widening the insulation thickness by 0.01 (dotted line) to 0.15 m (solid line) resulting in a final insulation thickness between 0.11 and 0.3 m. It is evident, that the energy saving efficiency of widening insulation thickness is lower when the original insulation d_0 is wider and vice versa.

Table 1 shows the result of the energy saving calculations at point D. The calculation of CO_2 equivalents savings at point D is given in Table 2. Widening the pulp insulation thickness d_0 of a well-insulated wall or ceiling from 0.15 m to 0.3 m saves 1,521 GJ ha^1. This is about sixteen times more energy than the energy gain of alternative A. Widening the pulp insulation thickness d_0 of a fair-insulated wall or ceiling from 0.1 m to 0.11 m saves even 5,310 GJ ha^1.

This is about fifty six times more energy than the energy gain of alternative A. In other words, the net energy gain of burning the yield of 1 ha RCG pays back within three years at point D and within one year only at point A. One may object that these considerable amounts of saved energy are accumulated over a period of 50 years.



Source: made by the author using equations (1) to (4)

Figure 3. **Ratio between saved energy E_s by insulation improvement and heat gain E_h of burning RCG as a function of the original insulation thickness d_0 and the insulation thickness increment Δd.**

Table 1

Calculation of the energy saving potential at point D of Figure 3

Process	Energy	Unit
Alternative A		
Gross energy yield of heat production from RCG: $6000\ kg\ ha^{-1} \cdot 17\ MJ\ kg^{-1}$	102,000	MJ ha^{-1}
Energy input of RCG production: $0.078\ GJ\ GJ^{-1} \cdot 102{,}000\ MJ\ ha^{-1}$	-7,956	MJ ha^{-1}
Net energy gain burning RCG	**94,044**	**MJ ha^{-1}**
Alternative B		
Energy input of RCG production	-7,956	MJ ha^{-1}
Energy input of paper production: $38\ MJ\ kg^{-1} \cdot 3{,}900\ kg\ ha^{-1}$	-148,200	MJ ha^{-1}
Energy gain from paper production waste: $6{,}000 - 3{,}900 = 2100\ kg\ ha^{-1} \cdot 17\ MJ\ kg^{-1}$	35,700	MJ ha^{-1}
Energy input of pulp production from recycled paper: $2{,}730\ kg\ ha^{-1} \cdot 3.25\ MJ\ kg^{-1}$	-8,873	MJ ha^{-1}
Energy gain from pulp production waste: $3{,}900 - 2{,}730 = 1{,}170\ kg\ ha^{-1} \cdot 17\ MJ\ kg^{-1}$	19,890	MJ ha^{-1}
Total energy input insulation production	**-109,439**	**MJ ha^{-1}**
Net energy gain by saving energy from additional insulation at point D of Figure 3	**1,521,256**	**MJ ha^{-1}**
EROI using RCG as insulation material at point D of Figure 3	14	MJ MJ^{-1}

Source: figures presented in chapter materials and methods

Table 2

Calculation of GHG mitigation potential at point D of Figure 3

Process and substitution alternatives	kg CO_2eq. ha^{-1}
Emissions from RCG production: $0.015\ kg\ CO_2eq.MJ^{-1} \cdot 102{,}000\ MJ\ \boldsymbol{ha}^{-1}$	1,530
Emissions from paper production: $1.1\ kg\ CO_2eq.kg^{-1} \cdot 3{,}900\ kg\ \boldsymbol{ha}^{-1}$	4,290
Emissions from pulp production of recycled paper: $0.2\ kg\ CO_2eq.kg^{-1} \cdot 2{,}730\ kg\ \boldsymbol{ha}^{-1}$	491
Total emissions	**6,311**
Mitigation from saved light fuel oil: $1{,}521{,}256\ MJ\ ha^{-1} \cdot 86\ g\ CO_2eq.MJ^{-1}$	125,108
Mitigation from saved natural gas: $1{,}521{,}256\ MJ\ \boldsymbol{ha}^{-1} \cdot 69\ g\ CO_2eq.MJ^{-1}$	98, 064
Mitigation from saved district heating: $1{,}521{,}256\ MJ\ \boldsymbol{ha}^{-1} \cdot 61\ g\ CO_2eq.MJ^{-1}$	86,654
Mitigation from saved electric power: $1{,}521{,}256\ MJ\ \boldsymbol{ha}^{-1} \cdot 190\ g\ CO_2eq.MJ^{-1}$	282,305

Source: CO_2eq of RCG: Lötjönen et al. (2009), CO_2eq of paper: Gromke and Detzel (2006), CO_2eq of pulp: Rakennustieto (2000), CO_2eq of fuels: Bremer Energie-Konsens GmbH (2006)

However, during the lifetime of 50 years, every year the harvest of RCG can be processed to paper and pulp. If the process of paper production is excluded and the yield of RCG is immediately processed to pulp for insulation purposes, the energy saving increases even more. It is evident that this energy saving figures are realistic in new construction buildings or under circumstances where the insulation improvement of existing buildings does not require additional demolition and construction work, e.g. improving the insulation thickness of a ceiling by blowing the pulp under the roof.

The *EROI* of alternative B reaches the magnitude of fossil fuels. However, if the indirect energy demand for RCG production, paper, and pulp production is taken into consideration, the *EROI* will drop below 10. Another aspect of energy saving and GHG mitigation is the replacement of mineral insulation material by pulp. The energy demand of rock wool production is about five times higher compared with pulp production from recycled paper (Rockwool International A/S, 2009). Thus, the 2,730 kg pulp ha^{-1} from recycled newspaper may save about 46 GJ needed to produce an equivalent quantity of rock wool resulting in a net energy gain of 37 GJ/ha.

Conclusions

The calculation example shows clearly that fibre crops should first be used as feedstock for industrial commodities before the residues are converted to energy at the end of the lifetime. Producing a table from a tree and burning the residues and the table at the end of its lifetime renders the same energy gain as using the tree for firewood only. Because of the second law of thermodynamics, decrease of entropy without energy input is impossible. Only the photosynthesis process, powered by sun energy, guarantees low entropy products for humans and animals. Thus, fibre crops processed and used as insulation material render an excellent example of high energy efficiency. The reason, why energy crops are recently used for fuels only, may be explained by agricultural subsidy policies, violation of basic thermodynamic laws, and neglecting both indirect energy input and external cost of energy crop production. Anyway, the energy return on investment of fossil fuels is still higher and therefore CO_2 mitigation using renewable energy sources is more expensive for the time being.

References

1. Bremer Energie-Konsens GmbH (2006) Checkliste-Einführung/Energieverbrauch, 2p. Available at: http://www.internet-energie-check.de/download/themenchecklisten/bek/Checkliste_allgemeiner_Energieverbrauch.pdf, 2nd January 2012
2. Doornbosch, R. and Steenblik, R. (2007) *Biofuels: is the cure worse than the disease?* Ed. Organisation for Economic Co-operation and Development. SG/SD/RT(2007)3REV1, 57 p. Available at: http://www.oecd.org/dataoecd/15/46/39348696.pdf, 2nd January 2012
3. European Environment Agency (2007). Estimating the environmentally compatible bioenergy potential from agriculture. *EEA Technical report No 12/2007*, Copenhagen, 136 p.
4. Fargione, J., Hill, J., Tilman, D., Polasky, S. and Hawthorne, P. (2008) Land clearing and the biofuel carbon debt. *Science,* 319, pp. 1235-1237.
5. Finell, M. (2003) The use of reed canary-grass (*phalaris arundinacea*) as a short fibre raw material for the pulp and paper industry. *Acta Universitatis Agriculturae Sueciae Agraria* 424,Umeå, 53 p. Available at: http://pub.epsilon.slu.se/378/1/Agraria_424_MF.pdf, 2nd January 2012, 2nd January 2012.

6. Finnish Forest Industries Yearbook, (2007) Finnish Forest Industries Federation, Helsinki 5/2007. Available at: http://www.metsateollisuus.fi/Infokortit/vuosikirja2007/Documents/Yearbook%202007.pdf
7. Finnish Meteorological Institute (2011) *Climatological statistics for the normal period 1971-2000.* Jyväskylä (62° 24`N 25° 40`E), Monthly statistics 1971-2000. Available at: http://en.ilmatieteenlaitos.fi/normal-period-1971-2000, 2nd January 2012.
8. Fritsche, U.R., Hünecke, K., Hermann, A., Schulze, F., Wiegmann, K. and Adolphe, M. (2006) *Sustainability Standards for Bioenergy.* WWF Germany, Frankfurt am Main, 80 p.
9. Gromke, U. and Detzel, A. (2006) *Ecological comparison of office papers in view of the fibrous raw material*. Institute for Energy and Environmental Research Heidelberg GmbH, Heidelberg, 40 p. Available at: http://www.papiernetz.de/docs/IFEU-Study_english.pdf, 2nd January 2012.
10. Hadders, G. and Olsson, R. (1997) Harvest of grass for combustion in late summer and in spring. *Biomass and Bioenergy,* 12, pp. 171-175.
11. ISO 6946 (1997) *Building components and building elements -- Thermal resistance and thermal transmittance -- Calculation method*. International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse CP 56, CH-1211 Geneva 20, Switzerland
12. Lötjönen, T., Pahkala, K., Vesanto, P. and Hiltunen, M. (2009) Reed canary grass in Finland. In: *Energy from field energy crops – a handbook for energy producers.* Jyväskylä Innovation Oy, Jyväskylä, pp. 14-22.
13. Mathews, J. (2007) Biofuels: what a biopact between north and south could achieve. *Energy Policy,* 35**,** pp. 3550–3570.
14. Mäkinen, T., Soimakallio, S., Paappanen, T., Pahkala, K. and Mikkola, H.J. (2006) Greenhouse gas balances and new business opportunities for biomass-based transportation fuels and agrobiomass in Finland. *VTT Tiedotteita - Research Notes 2357*, 134 p + app. 19 p. (in Finnish). Available at: www.vtt.fi/inf/pdf/tiedotteet/2006/T2357.pdf, 2nd January 2012.
15. Pimentel, D. (2008) Renewable and solar energy technologies. In: Pimentel D. (ed): *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*, Springer, Science+Business Media B.V., pp. 1-17.
16. Rakennustieto (2000) *RT Environmental Declaration* Ekovilla Oy, Ekovilla insulation material. Helsinki, 2p. Available at: http://www.ekovilla.es/gfx/pdf/ekovilla_environmental_declaration_24_es.pdf, 2nd January 2012.
17. Rockwool International A/S (2009) *Environmental Declaration ISO 14025.* Available at: http://www.epd-norge.no/getfile.php/PDF/EPD/Byggevarer/NEPD131ERockwool.pdf, 2nd January 2012.
18. Rydberg, T. and Haden, A. (2006) Emergy evaluations of Denmark and Danish agriculture: Assessing the influence of changing resource availability on the organization of agriculture and society. *Agriculture, Ecosystems and Environment,* 117, pp. 145-158.
19. Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Robertson, G.P., Schlesinger, W.H. and Tilman, G.D. (2009) Fixing a critical climate accounting error. *Science,* 326, pp. 527-528.
20. Smeder, B. and Liljedahl, S. (1996) Market oriented identification of important properties in developing flax fibres for technical uses. *Industrial Crops and Products,* 5, pp. 149-162.
21. Young, A.L. (2009) Finding the balance between food and biofuels. *Environmental Science & Pollution Research,* 16, pp. 117–119.

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