Global Land Use Implications of Biofuels: State-of-the-Art

Conference and Workshop on Modelling Global Land Use Implications in the Environmental Assessment of Biofuels

Jesper Kløverpris[1,2]*, Henrik Wenzel[3], Martin Banse[4], Llorenç Milà i Canals[5] and Anette Reenberg[6]

[1] Technical University of Denmark, Department of Management Engineering, Section for Innovation and Sustainability, Produktionstorvet, Building 424, 2800 Lyngby, Denmark
[2] Novozymes A/S, Sustainability Development, Krogshøjvej 36, 2880 Bagsværd, Denmark
[3] University of Southern Denmark, Institute of Chemical Engineering, Biotechnology and Environmental Technology, Niels Bohrs Allé 1, 5230 Odense M, Denmark
[4] Agricultural Economics Research Institute LEI – Wageningen UR, PO Box 29703, 2502 LS The Hague, The Netherlands
[5] Centre for Environmental Strategy, University of Surrey (D3), GU2 7XH Guildford, Surrey, UK; Current address: Unilever – Safety & Environmental Assurance Centre, Colworth Park, MK44 1LQ, Sharnbrook, Bedfordshire, UK
[6] University of Copenhagen, Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark

* **Corresponding author** (jklp@novozymes.com)

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Participants in the full event:
Group 1 (land use): John Beghin, Alessio Boldrin, Ingmar Jürgens, Ruben Lubowski, Jim Lynch, Llorenç Milà i Canals, Kjeld Rasmussen, Guido Reinhardt, Silvia Secchi, Bo Weidema, Rainer Zah
Group 2 (land use): Riina Antikainen, Mark Delucchi, Erik Steen Jensen, Freddy O. Nachtergaele, Yolanda Lechon Perez, Anette Reenberg, James Schepers, Ashbindu Singh, Peter Verburg, Henrik Wenzel
Group 3 (land use): Martin Banse, Christof Walter, Lew Fulton, Anton Haverkort, Sebastien Haye, Matt Johnston, Marianne Jönsson, Jesper Kløverpris, Huey-Lin Lee, Martin Persson, Rüdiger Schaldach
Group 4 (social aspects): Roland Clift, Pamela del Canto, Uwe Fritsche, Shabbir H. Gheewala, Michael Hauschild, Andreas Jørgensen, Eric Lambin, Markku Lehtonen, Gregory Norris, Peter Poschen, Dan van der Horst

Abstract

Background, Aims and Scope. On 4–5 June 2007, an international conference was held in Copenhagen. It provided an interdisciplinary forum where economists and geographers met with LCA experts to discuss the challenges of modelling the ultimate land use changes caused by an increased demand for biofuels.

Main Features. The main feature of the conference was the cross-breeding of experience from the different approaches to land use modelling: The field of LCA could especially benefit from economic modelling in the identification of marginal crop production and the resulting expansion of the global agricultural area. Furthermore, the field of geography offers insights in the complexity behind new land cultivation and practical examples of where this is seen to occur on a regional scale.

Results. Results presented at the conference showed that the magnitude and location of land use changes caused by biofuels demand depend on where the demand arises. For instance, mandatory blending in the EU will increase land use both within and outside of Europe, especially in South America. A key learning for the LCA society was that the response to a change in demand for a given crop is not presented by a single crop supplier or a single country, but rather by responses from a variety of suppliers of several different crops in several countries.

Discussion. The intensification potential of current and future crop and biomass production was widely discussed. It was generally agreed that some parts of the third world hold large potentials for intensification, which are not realised due to a number of barriers resulting in so-called yield gaps.

Conclusions. Modelling the global land use implications of biofuels requires an interdisciplinary approach optimally integrating economic, geographical, biophysical, social and possibly other aspects in the modelling. This interdisciplinary approach is necessary but also difficult due to different perspectives and mindsets in the different disciplines.

Recommendations and Perspectives. The concept of a *location dependent marginal land use composite* should be introduced in LCA of biofuels and it should be acknowledged that the typical LCA assumption of linear substitution is not necessarily valid. Moreover, fertiliser restrictions/accessibility should be included in land use modelling and the relation between crop demand and intensification should be further explored. In addition, environmental impacts of land use intensification should be included in LCA, the powerful concept of land use curves should be further improved, and so should the modelling of diminishing returns in crop production.

Keywords: Biofuels, increased demand; economic modelling; expansion; geography; land use changes; LCA

Introduction

The increasing production of first generation biofuels[1] such as biodiesel and bioethanol leads to an increasing demand for crops, which can only be satisfied by cultivation of more

[1] Oil, sugar or starch harvested from 'useful' parts of agricultural crops (e.g. oil, seeds, grain) are converted to biodiesel via transesterification (oils) and to bioethanol via fermentation (starches and sugars) (Lynch).

land and/or intensification of the existing crop production. On the other hand, second generation biofuels[2] have the potential to decrease the pressure on land as long as they are produced from by-products such as straw or maize stalks (see e.g. Jensen and Thyø 2007). In order to determine the environmental consequences of an increasing demand for biofuels, it is necessary to identify the areas ultimately affected by the increased utilisation of biomass (world region and specific local ecosystem). Such land use changes depend on several factors, including market mechanisms, the availability of new cultivable land, yield improvement potentials, and socioeconomic conditions. As the list indicates, the identification of ultimate land use changes caused by biofuels requires inputs from several disciplines and is not likely to be solved by the LCA community alone. This acknowledgement was the basis for an international conference and workshop entitled 'Modelling Global Land Use and Social Implications in the Sustainability Assessment of Biofuels', which was a follow-up of a smaller workshop organised in 2006 (Milà i Canals et al. 2006). The event took place in Copenhagen (Denmark) on 4–5 June 2007 and the aim was to bring together scientists from economy, geography, and LCA to discuss the modelling of land use changes caused by biofuels. Furthermore, social implications of biofuels were discussed.

The first day of the conference consisted of an open plenary session with 14 presentations of which 12 addressed land use implications of biofuels. Approximately 40 scientists (including the speakers) were invited to take part in a wrap-up and discussion session in the evening. On the second day, these scientists gathered for a workshop consisting of four parallel break-out sessions with additional presentations from the group members followed by discussions of the conference themes. Three groups discussed land use and biofuels and one group discussed social aspects of biofuels. The outcome of the break-out sessions was reported in a final plenary session.

This paper presents the basic background for land use approaches within economics, geography, and LCA and summarises and synthesises the main findings of the conference with relevance for land use modelling. It focuses on the land use issue but all abstracts from the conference (including those on social implications) are available in Kløverpris (2007) and the presentations are available at www.biofuelassessment.dtu.dk; they are referred to with the surname of the presenter only.

1 General Approaches to Land Use Modelling

Before the presentation of the results and the synthesis of the conference, a brief introduction is given to the approaches to land use modelling within the three scientific disciplines, economics, geography, and life cycle assessment.

1.1 The economic approach

The economic models of interest in this context represent the economy with a number of geographical regions, each containing a number of sectors. Partial and general models represent respectively part of the economy (e.g. the agricultural sectors) and the entire economy. The interplay between sectors and regions is determined by so-called elasticities expressing the relative change in one variable caused by the relative change in another variable. For instance, a 10 percent increase in the price for wheat in a given region may cause the wheat production to increase by 8 percent. Besides the elasticities, the models build on a wealth of other data types, e.g. tariff rates, production volumes, and data on existing trade flows.

An economic model represents an economic equilibrium (supply equals demand). A change in the economy (e.g. increased crop demand) can be studied by adjusting the relevant model parameters to simulate the change of interest. The model then adapts to the new conditions by establishing a new economic equilibrium. This adaptation is driven by price signals resulting in production changes in the different sectors. If the agricultural sectors are affected, changes in the use of land are also likely to occur. However, only some economic models include agricultural land utilisation as a variable. This variable may be determined by so-called land supply curves expressing the regional relationships between land price and land supply. Land supply curves are based on estimates of the land potentially available for production. However, not only land availability should be included in economic models, but also land heterogeneity. Therefore, some of the more advanced economic models rely on detailed biophysical and climatic information to determine land constraints. For instance, Birur et al. (2007) use agro-ecological zones (AEZs) in combination with an exogenous land supply following the methodology outlined in Lee et al. (2005). Furthermore, the general equilibrium model LEITAP (Klijn and Vullings 2005) is linked to the ecological-environmental modelling framework IMAGE (Alcamo et al. 1998) allowing feedbacks of biophysical constraints and the use of detailed heterogeneous information such as land productivity.

To model land use changes caused by biofuels, it is not enough to incorporate an endogenous land supply variable in the economic models. In addition, biofuels must be included in the economic models as commodities or as blends with fossil fuels in petrol. Therefore, economic researchers throughout the world are discussing various approaches to include first and/or second generation biofuels in their quantitative models. This requires incorporation of detailed links between the energy sector and agricultural activities and factors, especially agricultural land use. Some outcomes of these ongoing efforts were presented at the conference (see Section 3).

1.2 The geographical approach

The geographical approach to land use systems (incl. monitoring and modelling hereof) aims at establishing a general understanding of land use dynamics, land use patterns, and

[2] Plant cells from any source (e.g. straw, wood) are broken down via acid hydrolysis or enzymes to release sugars that are then fermented to produce bioethanol. Alternatively syngas (hydrogen and carbon monoxide) is produced which can then be turned into synthetic diesel via Fischer Tropsch process (Lynch).

land use driving forces. It corresponds well with land systems research in its most comprehensive form, which joins the human, environmental, and geographical information-remote sensing sciences in a discipline that seeks to improve:

- observation and monitoring of land changes underway throughout the world
- understanding of these changes as a complex coupled human-environment system
- spatially explicit modelling of land use and land cover change

There is a wide range of different geographical models. Recent decades' advances in remote sensing have contributed significantly with appropriate documentation of land cover at both local and global scale. Although considerable attention has been given to the spatial dynamics of land use, geographical models in general embrace a wide range of approaches such as spatial versus non-spatial; dynamic versus static; deductive versus inductive; agent based versus pixel-based; and global versus regional. An overview of the current practice in geographic modelling is presented by Verburg et al. (2004).

1.3 The LCA approach

In attributional LCA, the environmental assessment of biofuels is based on the direct suppliers of the necessary inputs to production. For instance, if ethanol is produced from European wheat, the land affected by biofuel production is assumed to be in Europe. Possible land constraints and displacement of other crops with its influence on land use elsewhere is thereby ignored. Furthermore, co-products are handled by allocation in attributional LCA. This means that the environmental impacts from biofuels production are simply split between the fuel and the co-products. It is thereby ignored that by-products from biofuels production often displace animal feed, which reduces the net pressure on land.

In consequential LCA, market mechanisms are taken into account and co-products are handled by system expansion. In principle, this means that all consequences of the change being studied (e.g. increased consumption of biofuels) are taken into account. Part of this procedure is to identify the marginal (as opposed to the direct) suppliers of inputs to production, i.e. those suppliers ultimately affected by changes in demand (Weidema 2003). Furthermore, the influence of co-products (e.g. displacement of animal feed) is included in the system modelling (Ekvall and Weidema 2004). It is typically assumed that the marginal suppliers have a single origin, e.g. a technology, country, or region.

2 Aspects of Importance for Modelling of Ultimate Land Use Induced by Biofuels Demand

Although consequential LCA, as a concept, is well suited for assessing the environmental impacts of an increased demand for biofuels, the practical application of the methodology still faces some challenges when it comes to identifying the land ultimately affected by increased biofuels production. Some of these issues are discussed in Kløverpris et al. (2008), a draft version of which was distributed prior to the conference to guide and inspire the debate on its most essential aspects:

Displacement-replacement mechanisms: When one crop displaces another, it is likely that the other crop (or a substitute) will be produced somewhere else thereby replacing the production lost due to the initial displacement. These dynamics are designated the displacement-replacement mechanisms.

Linear substitution: When a crop is displaced, an inherent feature of the LCA concept is to assume that it is fully replaced by production elsewhere. The replacement is based on functionality (e.g. nutritional value in case of animal feed products) and designated linear substitution.

Perfectly elastic supply: The increase in the production (supply) of a commodity caused by an increase in the price of that commodity is expressed by the supply elasticity. If consumption of a given product leads to an equivalent increase in production without affecting the rest of the market, the supply of that product is characterised as being perfectly elastic. The concept of linear substitution as well as LCA in general is based on an inherent assumption of products being in perfectly elastic supply. For instance, it is typically assumed that an increased use of biofuels will lead to an equivalent increase in crop production without affecting any other sectors using crops.

Diminishing returns: The crop yield per hectare is not proportional to the inputs to production (e.g. fertilisers). The more inputs applied to the field, the less is the additional increase in yield. This is characterised as diminishing returns.

Marginal crop production: The change in total crop production caused by a change in demand is designated marginal crop production. Changes in crop production happening independently of demand changes are not included.

3 Selected Results from Presentations

Kløverpris used a general equilibrium model to estimate the global agricultural expansion caused by a marginal increase in wheat consumption (as an example of increased crop demand caused by biofuels). Results demonstrated that the size of the global expansion heavily depends on where the wheat consumption takes place.

A general equilibrium model was also applied by Banse to show that agricultural land use within as well as outside the EU increases if mandatory blending is introduced. This expansion occurs especially in South America and might cause a decline in biodiversity in the countries affected.

Lee showed how agro-ecological zones (AEZs) can be incorporated in economic modelling to project the potential for GHG mitigation in agriculture and forestry. Her analysis shows that biophysical and economic land characteristics create comparative abatement advantages for land endowments.

Schaldach applied the spatial land use model LandShift for India to analyse the impact of biofuel crop production on land use at regional level. This analysis starts from a hypothesis that the cultivation of energy-crops will have a growing importance for India to fulfil the future energy demand. The first findings of this analysis identify a significant impact of bio-energy production on the spatial land-use pattern in India.

Verburg presented results based on the spatial land use model CLUE, which models geographic consequences. Results show that, in Europe, an enhanced production of biofuel crops will lead to less abandonment of cropland. However, cultivation is concentrated in a number of large regions with well-developed infrastructure and large areas of suitable arable land. These potential 'hotspots' of biofuel crop cultivation include NE Germany, parts of Poland, Lithuania, Czech Republic, agricultural areas around Paris, and around the border area of Slovakia, Hungary and Austria.

4 Selected Results from Break-out Sessions

It was generally agreed that an interdisciplinary approach to the modelling of land use changes caused by biofuels is necessary. Actually, it was mentioned that even more disciplines should have been represented at the conference, such as soil science and agronomy. Furthermore, it was stated that although we should strive to model the land use implications of biofuels, we should use models wisely by accepting their limitations and interpreting results with care. It was also pointed out that the models need to be transparent in order to use them in LCA.

Group 2 characterised the land supply curves used in some economic models (Kløverpris, Banse) as a powerful concept although problems with the calibration exist. Furthermore, the suitability of the agricultural land expressed by the land supply curves is not the only decisive factor. Infrastructure and social aspects also determine which land is the next to be used.

The ability of models to handle diminishing returns in crop production was also discussed. Apparently, this issue is taken into account by, at least, some models but only in a very general manner. There seems to be room for improvement concerning the algorithms and values used to model the correlations between input factors and yield.

Intensification and its interdependency on expansion was one of the main issues discussed. It was generally agreed that some regions in the third world hold large potentials for intensification, which are not realised due to a number of barriers in terms of local resource constraints (e.g. water and phosphorous) as well as no or low access to capital, knowledge, fertilisers, and markets. The lack of know-how leads to suboptimal crop yields seen in relation to the input of agricultural resources (water, fertilisers, pesticides etc.). This creates a yield gap (**Fig. 1**). Johnston is currently working on a quantification of the increased agricultural production that could be achieved if such yield gaps were closed.

Geographical differences influencing intensification were also discussed. Environmental legislation in the EU restricts the use of fertilisers, which means that higher crop prices will not result in higher yields achieved with more fertilisers. This is different in the US where a recent doubling of the corn price has changed the economic optimum of fertiliser inputs and, thereby, increased yields per hectare. These legal aspects must be accounted for in the modelling of land use changes.

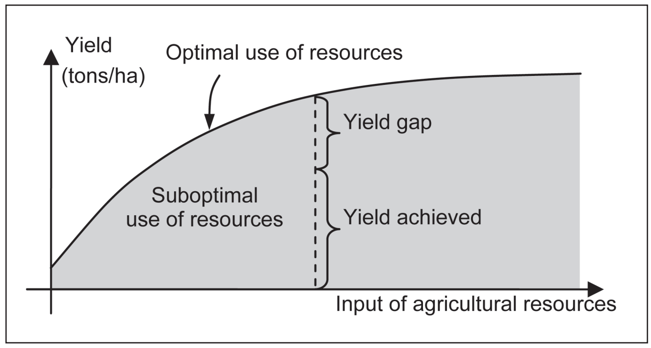

Fig. 1: Conceptual illustration of optimal use (the curve) and suboptimal use (the grey area) of agricultural resources and an example of a yield gap

Group 3 debated the trade-offs between expansion and intensification. Whereas expansion has negative impacts on natural habitats and thereby biodiversity, intensification may lead to other environmental impacts like eutrophication. To assess the environmental sustainability of biofuels, it is therefore necessary to determine the relationship between expansion and intensification caused by biofuels production and include it in the modelling of land use changes.

As to whether the increased demand for biofuels will lead to intensification by technological development in the form of improved crop strains, it was suggested that the biofuel demand may cause a new green revolution in which non-food GM crops are developed for rapid intensification to provide feedstock for biofuel production. Furthermore, the use of aquaculture was mentioned as a potential source of biomass. Algae in reservoirs can produce more biomass per hectare than land based crops and may even be a potential sink for CO_2.

In relation to the use of agricultural residues, it was stressed that only a certain share of this biomass resource can be removed from the soil if the fertility is to be maintained; this amount depends on local conditions. It was recommended to include soil carbon in the modelling of land use consequences derived from biofuel production (Milà i Canals).

5 Synthesis

Based on the results and discussions at the conference, we synthesise the findings relevant for life cycle inventory modelling of land use caused by the increased demand for biofuels.

5.1 Boundary conditions for the system modelling

The scale of the recent increase in the demand for biofuel raw materials (biomass) is large and the geographical scope is global (Beghin, Banse, Singh). This must be taken into account in the environmental assessment of the increased biofuels production. The scale itself has implications for the (marginal) suppliers responding to the new crop demand (Kløverpris, Banse, Beghin, Lambin). Moreover, due to the fact that crop markets are international and crops substitute each other within groups of similar chemical composition/nutritional value, increased demand for one crop influences the demand and supply on crop markets in general through the displacement-replacement mechanisms (Kløverpris, Beghin, Banse, Wenzel 2). Modelling the response to an increased demand for one crop therefore requires identification of other crops affected. At the conference, it became evident that many other crops in many regions of the world might be influenced when prioritising crops for biofuels in one country (Kløverpris, Beghin, Banse).

With respect to time scale, prioritising production of biofuels has implications for at least several decades, acknowledging the payback of investments in production facilities. In order to generate a solid platform for investments and for biofuel markets, the incentives generated must be kept robust for a longer period thereby implying a longer term prioritisation of crops for biofuels. To some extent we thereby luck ourselves into this crop prioritisation and biomass conversion pathway for several decades (Clift). This has implications for how we should model the consequences, in case biomass and land is constrained, because locking onto a certain technological pathway in this case means depriving ourselves the opportunity of using the same limited land or biomass in other technological pathways (Wenzel 1).

5.2 Biomass and land constraints

Biomass and land is of limited availability compared to the potential new customers for it being all sectors in society currently depending on fossil fuels (Wenzel 1, Reinhardt). The potential magnitude of biomass demand from these sectors is many times bigger than the current agricultural production. Today, agriculture is essentially producing food, and the energy content of foodstuffs consumed by the world's population is only around 6% of the energy content of the fossil fuels consumed by the world's population (Wenzel 1). As the growth in consumption of both food and energy is today higher than agricultural yield increases, increased crop demand is likely to result in new land cultivation but, according to Ramankutty et al. (2002), the current upper limit for new land cultivation is around a doubling (Wenzel 1). Much less than this can, however, be cultivated without transformation of protected natural areas (Delucchi, Wenzel 1). Any long term prioritisation of land and crops for one technological pathway will therefore happen at the expense of other uses of the same land and crop. The assessment of biofuels must therefore be seen in relation to alternative utilisation of biomass.

5.3 Marginal crop production

The conference demonstrated that even in some of the most advanced consequential LCAs, the approach to identifying marginal crop production is inadequate. When learning from the economic modelling, it seems clear that the assumption of a single most competitive supplier, in terms of a technology or region, does not hold true (see section 1.3). On the contrary, the changes in demand or supply of one crop influence the production of other crops in a variety of countries (Kløverpris, Beghin, Banse, Verburg, Wenzel 2). The reason is that several suppliers will respond to changes in crop demand and that the relative contribution from the marginal suppliers due to tariffs, transportation costs and other trade barriers will depend on the geographical location from where the change in crop demand originates. All these factors determine the marginal land use response to increased biofuel demand. We therefore introduce the concept of a *location dependent marginal land use composite*, i.e. the sum of global agricultural land use expansion caused by biofuel demand originating from a specific location. This is one issue where the LCA society could benefit from economic modelling.

5.4 Linear substitution

Results presented at the conference indicated that the demand for biofuels will affect crop prices in more than just the short term (Banse, Beghin). This shows that the supply of crops is not perfectly elastic and that linear substitution (see section 2) cannot necessarily be assumed in the modelling of land use changes caused by biofuels. This is also an issue on which the LCA society could learn from economic modelling.

5.5 Demand driven intensification

When striving to follow the displacement-replacement flows, a key uncertainty factor is the role of intensification (Wenzel 2). It was widely discussed at the conference, how much of the response to an increase in demand, one should attribute to intensification, i.e. increase in crop yields per hectare. Intensification partly occurs independent of demand (e.g. due to continuous competition) and partly due to price increases and R&D motivated by perceived threats and opportunities based on the development in demand (Wenzel 2). The conference did not result in any clear recommendations for how to handle the relation between demand and intensification in the modelling of land use changes caused by biofuels. This remains a crucial point for further clarification.

5.6 Contributions from the field of geography

The field of geography offers at least two important contributions to the modelling of land use changes caused by biofuels production. It provides spatially explicit datasets of land use and land cover, which can be used in the construction of land supply curves and in the assessment of the areas affected by increased cultivation of land. The geographical approach also offers an understanding of land use dynamics, which goes beyond the neoclassical supply and demand mechanisms. This insight can also help to refine predictions of land use changes caused by biofuels.

6 Conclusions

In order to carry out life cycle assessments of biofuels, there is a need for modelling of the related land use consequences. So far, the general LCA approach to land use modelling has been based on functionality of products and by-products and an implicit assumption of linear substitution. In consequential LCA, the ambition is to identify marginal suppliers of the crops affected by biofuel consumption. However, the methodology needs further refinement. The economical approach is based on price signals caused by the demand for biofuels. The increasing prices lead to increasing production of biomass, which is achieved by a combination of intensification and expansion. In some economic models, the price of land is determined by land supply curves and thereby factored in. The geographical approach is broader combining human, environmental, and geographical information-remote sensing sciences with the aim of establishing a general understanding of land use dynamics, land use patterns and land use driving forces. The modelling of land use consequences of biofuels requires an interdisciplinary approach optimally integrating economic, geographical, biophysical, social and possibly other aspects in the modelling. This approach is necessary but also a challenge due to different perspectives and mindsets in the different disciplines.

It was generally agreed that there is a huge intensification potential if agricultural inputs were used optimally and third world countries had better access to the world market. This means that biomass production can be increased significantly without further expansion of the agricultural area. However, the intensification of land use may have other consequences, e.g. loss of soil carbon and increased leaching of nutrients, which should be taken into account in the environmental assessment.

The land supply curves applied in some economic models constitute a powerful concept in land use modelling although the calibration of the curves could still be improved. Likewise, the ability of economic models to handle diminishing returns in crop production also holds room for improvement.

As for environmental modelling (LCA), the concept of a *location dependent marginal land use composite* should be introduced as an expression for the sum of agricultural land use expansion caused by biofuel consumption in a given location. Furthermore, the implicit assumption of linear substitution typically applied in LCA should also be reconsidered as the supply of biomass is not perfectly elastic. Economic models can be helpful in this aspect.

It is recommended to incorporate (possibly more transparently) restrictions on the use of fertilisers as well as accessibility to fertilisers in the economic models. The clarification of the relation between demand and intensification also requires more research. Furthermore, the modelling of land use changes in a broader sense should build in constraints caused by scarcity of resources (e.g. land, water, and phosphorous) and take into account the value of ecosystem services (e.g. water filtration). Finally, models should be used wisely and not trusted blindly.

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