Forecasting the magnitude of sustainable biofeedstock supplies: the challenges and the rewards†

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Introduction

The uncertainty surrounding the bioenergy industry’s future significance is a major challenge facing the nascent industry and policy-makers evaluating the merit of that industry in the context of economic value, energy security, and mitigating climate change. Will bioenergy stay a niche technology or could it make a truly significant contribution to the US or global energy sector? And if it did, could it do so in a manner that was sustainable...
in the broadest context of the word – economically, socially, and environmentally? In addressing these questions, the magnitude of sustainable biofeedstock supplies is paramount. The significance of the industry ultimately rests on the amount of feedstock it can obtain sustainably and without threatening other competing land uses (food, feed and fiber production). However, forecasting supplies in a way that captures the economic and environmental factors that will dictate supply magnitude and sustainability has proven challenging. In this perspective, we outline how estimates of biomass supply have evolved in the USA, discuss the environmental and economic factors that need to be considered, and point to new capabilities that will enhance our ability to forecast biomass supplies and their attendant economic and environmental implications. We use the term ‘sustainability’ in the context of the Brundtland report which defines sustainable development as: ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’.

Thus in the parlance of this perspective, economic sustainability refers to the notion of economic viability, and environmental sustainability refers to the notion of preserving environmental values. We also adopt a more general use of the word ‘supply’ rather than the economic use, which implies both price and quantity.

**Past US forecasts**

An examination of past US feedstock assessments provides insight into the evolution of feedstock supply forecasts and how sustainability considerations have been addressed. Taking a US perspective, one of the earliest quantitative assessments which considered land quality and its effects on yield and suitability for feedstock production was published by Graham in 1994. In her article, Graham quantified the land base suitable for energy-crop production in the USA without irrigation using geographically specific information on soil characteristics. She estimated that 156.8 million hectares of US land were suitable for energy-crop production on this land, 2,332 million Mg of feedstock from herbaceous energy crops or 1,698 million Mg of feedstock from woody energy crops could be produced annually given no barriers to biomass production other than climate, soil quality, and suitability for agriculture. Relying on agricultural suitability ratings to define environmental sustainability and giving no consideration to price or competing land demands for food and feed production, the assessment defined an upper bound on the land base suitable for energy-crop production, pulled together expert opinion (at that time) on potential energy-crop yields across the USA, and described regional variations in potential crop supply.

A later assessment of energy crops in the USA addressed economic sustainability and current crop conditions and considered the interplay between demand and prices for both conventional and energy crops. Walsh et al., used an agricultural sector model that captures economic constraints to production (POLYSIS) to estimate the potential supply of feedstocks from energy crops. Although this assessment did not explicitly address any specific environmental considerations – such as erosion, wildlife or water quality – it did capture considerable spatial variability in crop production and yields by modeling the USA as 305 unique agricultural production regions. The study approached the question of energy-crop supply by simulating the agricultural sector’s response to a suite of farmgate prices for biomass feedstock from energy crops. This study estimated that over the time period of analysis (2000–2008) a farmgate biomass price of ~$43 per dry Mg could result in 17 million hectares planted to switchgrass producing ~ 170 million dry Mg of switchgrass annually – a considerably lower estimate than that of Graham.

Very recently, using a more spatially aggregated approach – 63 regions to cover the USA – that blended both economic and environmental considerations, McCarl and Sands examined the reduction of greenhouse gas (GHG) emissions associated with production of energy from US biomass feedstocks. This analysis took into account both GHG emissions associated with crop production practices and soil carbon changes. The analysis linked a forest and agricultural sector model (FASOMGHG) with an economy-wide general equilibrium model (SGM) that considered energy technologies and net GHG emissions associated with those technologies. The authors simulated scenarios with differing CO₂ prices and quantified the overall utility of several terrestrial mitigation technologies, including bioenergy, for reducing GHG emissions. The relative merits of five terrestrial carbon mitigation technologies were compared: bioenergy, forest...
management, afforestation, soil sequestration, and energy-crop management. At a carbon price of $30 per Mg of CO$_2$ bioenergy – feedstock production and use – reduced GHG emissions more than the other four options did.

The POLYSYS and FASOMGHG analyses addressed sustainability concerns over a large spatial extent and at a fairly coarse spatial resolution. Other forecasts of biomass feedstock supply have focused on local environmental conditions by using a finer spatial resolution. In particular, erosion associated with removing crop residues has been studied at finer scales. In 2007, working with an approach pioneered by R. Nelson and J. Sheehan, Graham et al., examined the cost and collectable amount of stover produced in the USA in an analysis based on 1995–2000 corn-production patterns at a county-level, and soil type at a sub-county resolution. In 2003, Gallagher et al., also tackled the questions of sustainable corn-stover supplies with a focus on erosion considerations and Wilhelm et al., examined the same notion in a less-quantitative fashion in their 2004 review of the crop and soil productivity concerns associated with corn-stover collection. All concluded that the USA would have a significant supply of corn stover suitable for biomass feedstock even if constrained by the need to leave sufficient stover in the field to control erosion.

Environmental constraints to supply were indirectly considered in the recent study by Perlack et al., which brought together, in one document, estimates of potential supplies of all feedstock types in the USA by the mid-twenty-first century. This study focused on the question of whether the US forest and agricultural land base could produce one billion tons of biomass feedstock annually and still meet projected food, feed, and fiber demands. Estimates of agricultural residues available for feedstocks were tempered by considering the need to leave some residue in the field for erosion control. In the case of feedstocks from forest resources, supplies from thinning to reduce fuel loads in forests were constrained by topographic conditions (steep slopes) and proximity to roads. The only economic consideration addressed was a requirement that projected agricultural food and feed demands be met from the US land base. While this analysis concluded that a billion-ton annual supply was feasible, other analyses have been less optimistic; Gallagher, taking a more near-time perspective and considering farm prices, concluded at best the US land base could support an annual supply of ~700 million Mg/year.

In looking over the last 15 years of US assessments, it is evident that forecasts of potential biomass feedstock supplies have evolved to capture an increasingly wide range of economic and environmental considerations.

### Challenges to forecasting economic and environmentally sustainable feedstock supplies

Forecasting the magnitude of environmentally sustainable supplies is challenging because of complexity in the biology and production of feedstocks and the wide assortment of environmental considerations including erosion, water quality and quantity, biodiversity, wildlife, air quality, and soil carbon. The choice of feedstock, and how it is managed, has profound effects on the available sustainable supply and its cost. Questions regarding sustainability also depend on scale because environmental responses to biomass production depend on the scale of analysis. Finally, to fairly judge environmental consequence, analyses should compare producing biomass feedstocks to maintaining the status quo or the likely alternative.

### Feedstock choice and management

The blessing of bioenergy is that there are so many different types of feedstock. The bane of bioenergy assessments is that there are so many different types of feedstock. Each feedstock presents different environmental and economic considerations. This complexity is magnified by the fact that most feedstocks can be produced in multiple ways. The study by Perlack et al., offers a useful construct for considering the complexity of potential feedstocks (Fig. 1). It differentiates feedstocks first on the primary resource base from which they are derived (for example, forest or agricultural land) and then on whether the feedstock comes directly from the land (for example, energy crops or crop residues), remains as a by-product or residue from a processing industry (for example, forest-mill residues or pulping liquors), or is a waste from consumption of a final product (for example, urban wood waste or waste grease). In the remaining discussion, we use this construct to discuss specific environmental constraints (and benefits) associated with feedstock supplies.
Like the Perlack et al., study, we will focus on primary biomass supplies because they are the most important in terms of magnitude and sustainability.

Supplies from forest lands

If we consider the supply of biomass from forests, key environmental sustainability concerns include nutrient removal, compaction of soil, machine damage to remaining trees, and changes in stand structure – species, density, size classes and understory. The latter two concerns apply largely to forest biomass resources that result from the thinning of forests to reduce fuels and the risk of intensive wildfires. A major concern, and one more difficult to forecast, is the building of new forest-access roads and the associated problems with road construction – erosion and habitat fragmentation. Although some of these concerns can be mitigated by good forest management and road construction practices – erosion, soil compaction, machine damage and nutrient removal – other concerns, such as habitat fragmentation, are largely unavoidable. None of these concerns are easy to quantify or to model. Consequently, forest resource assessments have largely addressed these issues by assuming the use of best management practices during harvesting activities.

Thinning forests for fuel reduction and biomass production has some potentially major environmental benefits, especially in the western USA where fires in overstocked forests are an environmental and social concern. Intense wildfires can lead to air pollution, major CO₂ emissions, excessive erosion, temporary reductions in water quality, habitat loss, and severe depletion of soil nutrients and carbon. These consequences have propelled some to strongly advocate the development of bioenergy industries in the western USA as a means of reducing wildfires. The environmental and social consequences of a bioenergy industry relying on forest thinning are quite complex, however, with many direct and indirect effects and feedbacks as illustrated in Fig. 2 taken from Graham et al. To truly understand the net benefits and risks of thinning to reduce fuel loads requires recognizing all the downstream effects and their feedbacks. Furthermore, although the conceptual linkages are understood, quantitative models for addressing the relative benefits and liabilities of using thinning – and thereby producing biomass supplies – to reduce fire-fuel loads are frustrated by a lack of metrics for many of the environmental variables. Stand structure and hydrological influences are, however, two considerations that have been addressed, at least in the Sierra Nevada. Using a hydrology model, Huff et al., found that thinning to reduce fuel loadings had little impact on the hydrology of forest watersheds except in low-elevation watersheds with minimal snowpack. In a related modeling study of long-term stand structure, Hollenstein et al., determined that the supply of feedstock resulting from stand thinning would stabilize after the initial thinning but the removal of at least 10% of the large trees during the thinning process was necessary to ensure stand stability, fire resilience, and continuing supply of biomass feedstock.

Supplies from agricultural land

The environmental sustainability concerns associated with feedstocks from agricultural lands overlap with those associated with feedstocks from forest thinning. As with forest supplies, key environmental concerns include erosion, depletion of soil nutrients, reduced water quality, and loss of wildlife habitat. However, concerns about the effects on soil carbon and invasive species become more significant in agricultural systems. The choice of feedstock and its management profoundly determines the environmental outcome of agricultural supplies. Agricultural feedstocks can be grouped into four types:
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1. annual grain and oilseed crops – for example, corn [Zea mays], soybeans [Glycine max]);
2. residues from annual crops – for example, corn stover, wheat [Triticum aestivum] straw);
3. annual crops harvested for their biomass – for example, sweet sorghum [Sorghum bicolor]; and
4. perennial crops encompassing both grasses – switchgrass [Panicum virgatum], Miscanthus [Miscanthus x giganteus] – and trees – hybrid poplar [Populus spp.] and willow [Salix sp.]).

Erosion impacts can be serious for all four feedstock types, but especially for residues from annual crops. More research has been done on this topic than on any other. No-till or reduced-till agriculture can mitigate erosion problems in some cases, but not all. Graham et al., estimated that universal adoption of no-till would almost double the amount of stover that could be removed in the USA without excessive erosion. Even with the use of universal no-till management practices, however, it was estimated that 40% of the US stover would still need to stay in the field for erosion control; for individual soil types this percentage varied from 5% to 100%. In comparison, perennial biomass crops are noted for protecting soil and generally represent a significant improvement over conventional annual crops, although erosion can still be a problem during their establishment. Erosion during this phase can be mitigated through the use of cover crops – in the case of woody perennials – or by establishing grass crops without tillage.

Soil-carbon loss with the removal of residues, especially if the crop is tilled, is another area of concern that has received significant attention as it has impacts on long-term productivity of the soils and GHG emissions. With the widespread adoption of reduced-tillage and no-till production systems, soil carbon on US agricultural lands is now being restored. It is not clear to what extent the partial removal of crop residues that are currently allowed to decompose in situ would reverse this trend. Johnson et al., estimated on the basis of several long-term field trials that leaving 1.8 Mg C (from residues) ha⁻¹ yr⁻¹ was necessary to maintain soil organic carbon under no-till or conservation-tillage systems.
Although there are models suited to the analysis of these concerns, they are much more complex than the models used to evaluate erosion and thus have not been applied to the same extent. Sheehan et al., did utilize the Century model to estimate soil carbon changes in Iowa under a shift from current conditions to no-till continuous corn production, harvesting stover but leaving sufficient amounts to control erosion. They concluded that if they met the erosion constraint – an average of 2.46 Mg stover ha\(^{-1}\) yr\(^{-1}\) in Iowa – the remaining stover could be removed without impairing future crop yields even though soil carbon did initially decrease. There is good evidence that perennial crops, both grass and woody, with their substantial root systems, considerably enhance soil carbon – in many cases on the order of 1 Mg C ha\(^{-1}\) yr\(^{-1}\).15–16

A third area of concern is water quality because of the need to apply fertilizers to enhance crop yields and replace nutrients removed with crop harvest. This concern has been raised particularly for stover harvesting, a production system that removes most of the nutrients contained in the crop. Perennial crops are largely viewed as more benign because they require significantly less fertilizer than most conventional agricultural crops and if planted strategically in the landscape adjacent to waterways could actually improve water quality. Fertilizer demand can be reduced in perennial grass crops by harvesting only once a year after leaf senescence and retranslocation of nutrients to the roots and rhizomes has occurred. Up to half of the nitrogen content of the stem and leaf tissues is retranslocated to the root system each year if the plant is allowed to senesce before harvest. Woody crops, which also retranslocate their nutrients each year and are likely to be fertilized just a few times during their multi-year rotation, are especially viewed as offering opportunities to improve water quality.

Finally, our understanding of potential impacts of biofeedstock production on wildlife habitat and the spread of invasive species is in its infancy. Data and metrics for comparing different feedstocks and management strategies in the context of these two factors are largely unavailable although there has been some work investigating wildlife use of perennial crops, especially woody perennials.20 The results of this work on poplar plantations suggested that wildlife use is a function of the surrounding landscape, the field size, the age of the energy crops, and plant diversity in the understory. Here again, management practices used in the crop production – for example, field size and weed control – influence the environmental outcome of the crop production.

A major challenge to forecasting agricultural supplies is optimizing across the many available options. For any piece of land there could be ten or more unique feedstock/management options that could be applied. Even simply optimizing with economic objectives – for example, production cost – is non-trivial. Adding environmental considerations contributes another layer of complexity as there are neither standard metrics to quantify many environmental influences – a pre-requisite for including environmental objectives in optimization models – nor universally accepted ways of comparing across metrics. Multi-objective optimization methods can be subjective because the various goals must be assigned weights – weighing biodiversity against erosion or against production cost. Nonetheless, an important benefit of applying such optimization methods is the ability to evaluate tradeoffs between economic and environmental objectives, and among various environmental objectives. An alternative approach is to set environmental constraints on the optimization problem, maximizing an economic objective while meeting specified – and potentially multi-faceted – environmental targets. Analyses of this sophistication have not yet been applied to the challenges of forecasting sustainable national biomass feedstock supplies. To date, a much more limited approach has been taken in which potential feedstock production is limited to only those management conditions that meet a set erosion or soil-cover threshold7–8 and then economic criteria are applied to determine cost and/or where feedstock production would occur.

**Resources vary with geography and scale**

Apart from the complexity of considering multiple feedstocks and their myriad management options when estimating potential feedstocks, one is also faced with the dilemma that both the economic and environmental characteristics of production vary with geography and scale of production. Land value, a major determinant of feedstock production cost, shows enormous geographic variation. Capturing that variation is challenging because land value is a function of all the alternatives for which the land

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could be used. Another economic variable with significant geographic dimensions is transportation cost. Regions with a low density of feedstock production have higher transportation costs as do regions with low road density. Perlack and Turhollow examined the effects of resource density on transportation cost at a landscape level for the collection of corn stover. Low resource density could add up to $10.80 per dry Mg in additional costs for the scenarios they evaluated. Likewise, environmental factors vary geographically. For example, wind erosion is a potential problem in some regions but not in others. Graham et al., found that wind erosion would largely preclude stover collection in several states unless no-till agriculture was adopted. Another geographically sensitive concern is the leaching of fertilizers to streams and rivers. For a given crop and application of fertilizer, this phenomenon varies with climate and soil type. Fertilizer loss to streams can be strategically mitigated by growing perennial energy crops as buffer strips near streams and relying on the more complex root systems of those crops to take up the fertilizer lost from annual crops planted upslope. Assessing the opportunity and the cost of producing perennial energy crops in this fashion is, however, not easy and requires detailed geographic information coupled with production costs associated with managing strips rather than the usual blocks of land.

Scale of analysis is also a consideration for both economic and environmental factors. At a local scale one does not need to consider how the market price of different competing crops will be affected by the conversion of land to energy-crop production. Feedback at this scale is minimal. In contrast, at regional and national scales, these feedbacks need to be considered as converting millions of hectares from one crop to another or increasing the value of a crop such as corn by creating a market for its residue will have significant price implications.

If we turn to environmental factors, we find the same need to consider scale. This is particularly true for issues related to water quality. At a field scale, the water quality effects of different crop management strategies may not be apparent but at a watershed scale they will be evident in higher or lower nutrient loadings in streams, possible algal blooms, and changes in stream and river biota. Some effects on water quality from changing fertilization practices or reducing erosion are not manifested except at regional scales. Hypoxia, the lack of oxygenated water, in the Gulf of Mexico is largely a consequence of fertilization practices in the Mississippi basin and has negative effects on aquatic life in the Gulf as well as the fishery and recreation industries that depend on it. There is considerable concern that high corn demand for ethanol production and the attendant increase in continuous corn rotations and fertilizer use in corn-dominated watersheds will exacerbate the already problematic situation. Even effects on water quantity are scale dependent. Huff et al., showed that forest thinning for fuel reduction and biomass production in the Sierra Nevada could have significant hydrological effects on some small watersheds, but at large watershed scales the effects were muted by the pattern of forest cover and ownership in the region. Capturing these scale-dependent effects are difficult, but with the advent of more powerful geographic information systems and wider availability of spatially explicit information on land use, soils, and topography combined with better process-oriented models, assessments are beginning to tackle these issues. For example, in 2006, the SWAT model was used to forecast the effects of producing switchgrass on water quality at a watershed scale in northeast Kansas.

Change in land use
To assist policy-makers and the public in evaluating bioenergy, it is also important to quantify the changes that bioenergy production induces. This requires comparing the forecasted outcome with the current situation or an alternative future without a bioenergy industry. This is especially important for addressing environmental sustainability. Policy-makers need to know the direction and magnitude of the change, not just the situation after the change. For example, the environmental consequences of converting land currently in corn-grain production to switchgrass production are quite different from the environmental consequences of converting unmanaged pasture into switchgrass even though both result in the establishment of a perennial grass. In the former case, the direction of change is toward increased sustainability on virtually all fronts; in the latter case, the direction of change is toward decreased sustainability, at least with regards biodiversity and fertilizer use. The costs of those transitions are also different, with
greater costs associated with converting pasture to energy crop. Current land use profoundly impacts the relative benefits and costs of biomass feedstock production. Graham et al., illustrated this in an analysis of switchgrass production in the state of Tennessee.24 This study cited hypothetical bioenergy facilities based on delivered cost of feedstock and evaluated using the EPIC model, a suite of environmental effects associated with the land-use changes induced by supplying those facilities with switchgrass. There was a two-fold factor of difference in the range of environmental outcomes of supplying the eight facilities even though all the facilities used the same quantity of feedstock.

Analyses like the ones above are uncommon. With improvements in underlying data (more information and finer spatial resolution) and advancements in process models for predicting existing and future conditions, it should become easier to assess the long-term sustainability of a bioenergy industry at regional and larger scales.

Conclusions

Our capabilities to assess sustainable feedstock supplies are improving but much more work needs to be done. Future assessments will need to rely heavily on geographic information systems and underlying maps of roads, soils, climate, topography, and land use to capture spatial variability. Fortunately land-use data are improving, as is the availability of digital maps describing the other variables. Mechanistic, process-oriented models of crop and forest production that explicitly consider the environmental and economic factors of concern – for example, soil erosion, soil carbon, nutrient loss, feedstock yield, feedstock production cost – are needed both alone and coupled to hydrologic watershed models to understand changes in water quality and water quantity induced by bioenergy-driven land-use changes. These models will need to be linked to agricultural and forest sector models that can analyze and optimize the interactions of multiple crops and differing forest management activities.25 While significant advancements relevant to forecasting sustainable biomass production have been made in process-oriented models such as EPIC, Century, SWAT and sector models such as POLYSYS and FASOMGHG, there is still need for future improvements. Underlying all data and modeling capabilities, there must be more field research and measurements to provide the necessary parameters and algorithms to these models and enable the creation of metrics useful for comparing different biomass supply systems.

Future forecasts of sustainable biomass supplies will not be easy or inexpensive to do. They will involve coupling models and data in new ways and linking environmental scientists with economists but the potential rewards are enormous. With previous massive land-use changes in the USA, there was no a priori consideration of sustainability – for example, plowing of the prairie in the 1800s, shifting to soybean production in the 1900s. For the first time, we have the opportunity to provide decision-makers with analyses that will enable them to evaluate the environmental and economic tradeoffs of using myriad alternative biofeedstock supplies. We have the opportunity to enable the nascent bioenergy industry to move forward and deliberately capture the potential environmental and economic benefits of biofeedstock production and reduce the potential risks. Let us hope we seize that opportunity.

Acknowledgement

This research was supported by the US Department of Energy’s Biomass Program within the Office of Energy Efficiency and Renewable Energy. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the US Department of Energy under contract DEAC05-00OR22725.

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