Mobilizing Sustainable Bioenergy Supply Chains

Inter-Task Project Synthesis Report

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Mobilizing Sustainable Bioenergy Supply Chains

Strategic Inter-Task study, commissioned by IEA Bioenergy

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KEY MESSAGES

Analysis of the five globally significant supply chains conducted by IEA Bioenergy inter-Task teams – boreal and temperate forests, agricultural crop residues, biogas, lignocellulosic crops, and cultivated grasslands and pastures in Brazil – has confirmed that feedstocks produced using logistically efficient production systems can be mobilized to make significant contributions to achieving global targets for bioenergy. However, the very significant challenges identified in this report indicate that changes by all key members of society in public and private institutions and along the whole length of supply chains from feedstock production to energy product consumption are required to mobilize adequate feedstock resources to make a sustainable and significant contribution to climate change mitigation and provide the social and economic services possible. Notably, this report reveals that all globally significant bioenergy development has been underpinned by political backing, which is necessary for passing legislation in the form of mandates, renewable energy portfolios, carbon trading schemes, and the like. The mobilization potential identified in this report will depend on even greater policy support than achieved to date internationally.

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EXECUTIVE SUMMARY

1 THE CHALLENGE

Significant opportunities exist to reduce greenhouse gas emissions, increase domestic energy security, boost rural economies, and in some cases improve local environmental conditions through the deployment of sustainable bioenergy and bio-based product supply chains. There is currently a wide selection of possible feedstocks, a variety of conversion routes, and a number of different end products that can be produced at a range of scales. However, economic slowdown, low oil prices, lack of global political will, and lingering questions regarding land use change provide a challenging global context to speed the pace of investment.

There are a number of social, economic, institutional and technical barriers to market penetration of bioenergy that will need to be overcome in order to realize opportunities on a wider scale. Some of the most significant barriers include issues related to supply chain complexity and cost, including logistics and intermediate storage, competition for biomass raw materials for different end-uses, market development and penetration, confidence in feedstock inventory estimates, development status of prospective conversion technologies, and satisfying a growing number of sustainability requirements.

2 THIS REPORT & TEAMS INVOLVED

This report provides a synthesis of key messages that are derived from very extensive underpinning documents written by over 70 colleagues from around the world with many decades of experience in all aspects of sustainable bioenergy production systems. It summarizes the results of an IEA Bioenergy inter-Task project involving collaborators from Tasks 37 (Energy from Biogas), 38 (Climate Change Effects of Biomass and Bioenergy Systems), 39 (Commercialising Conventional and Advanced Liquid Biofuels from Biomass), 40 (Sustainable International Bioenergy Trade: Securing Supply and Demand), 42 (Biorefining – Sustainable Processing of Biomass into a Spectrum of Marketable Bio-based Products and Bioenergy), and 43 (Biomass Feedstocks for Energy Markets). The purpose of the collaboration has been to analyze prospects for large-scale mobilization of major bioenergy resources through five case studies that determine the factors critical to their sustainable mobilization. The following bioenergy resources have been analyzed, with special focus on selected countries and regions that cover different conditions:

- forest biomass in temperate and boreal ecosystems, including a broad range of countries and conditions;
- agricultural crop residues focusing on supply chains in Denmark, the United States of America and Canada;
- biogas production from municipal solid and liquid waste, oil palm residues, and co-digestion of agricultural crops and residues and animal wastes;
- lignocellulosic crops in agricultural landscapes, with special attention to their place in sustainable landscape management and design; and

- bioenergy involving feedstock cultivation on pastures and grasslands, with special focus on sugarcane ethanol in Brazil.

Several different novel and existing frameworks of analysis have been used in the case studies to develop an operational, business and policy-based understanding in order to explain the factors that contribute to globally significant sustainable supply chains. They include elements of techno-economic analysis, availability of feedstock, applicable conversion processes, GHG balances, land use issues, governance mechanisms, and other aspects of bioenergy production and supply. Sustainability impacts evaluated include environmental, legal, economic, and social considerations. The analytical approach used in this project has allowed the authors to integrate numerous regional and national perspectives in their work across the complex systems which aim to support transfer of knowledge to new and upcoming bioenergy technologies and feedstock mobilization in different regions of the world.

3 CURRENT STAGE OF DEVELOPMENT FOR SIGNIFICANT GLOBAL BIOENERGY SUPPLY CHAINS

Biomass supply chains and conversion technologies are in various stages of commercial readiness and exhibit different levels of complexity; therefore, the applicability and extent of the barriers listed above varies from supply chain to supply chain. Understanding the various sustainable feedstocks and conversion pathways leading to biofuels, bioenergy, and co-produced bio-based products is crucial to overcoming these barriers and developing an effective business case for emerging industries. Energy market penetration depends heavily on the existing energy profile of a country, oil prices, the rate of energy technology development (outside of bioenergy), and the existence of mandatory government targets and incentives to promote renewable energy (e.g., the EU Renewable Energy Directive of 2009).Energy market penetration depends heavily on the existing energy profile of a country, the rate of energy technology development (outside of bioenergy), and the development of government targets and incentives to promote renewable energy (e.g., the EU Renewable Energy Directive of 2009).

One of the major challenges to realizing mobilization potential is that biomass supply infrastructure has not yet been fully established in many parts of the world. Efficient and commercially viable conversion technologies are also lacking for a number of supply chains and regions; and the valuation of by-products and co-products such as CO_2, ash, lignin is often lacking. Furthermore, the willingness of stakeholders to invest in infrastructure and technology is challenged by uncertainties surrounding long-term feedstock supply of both crops and value chain residues. This variability is due to different operational, sustainability, and conversion constraints acting along specific supply chains, which must be better understood to develop a realistic resource assessment.

4 INSTITUTIONAL CHALLENGES & DRIVING FORCES

Barriers to mobilizing bioenergy supply chains are not only present in the technologies and the economics of logistical systems, but also in institutional development. Review of country experiences generally shows that almost all significant bioenergy development has political backing which is necessary for passing legislation in the form of mandates, renewable energy portfolios, carbon trading schemes, etc. Policies need to be coordinated across departments (e.g., forestry, agriculture, energy, environment, and climate change) to support and govern emerging bioenergy systems. Comprehensive and scientific guidelines, regulations and standards must ensure that increases in biomass outputs respect sustainability considerations, which also need to be better understood. One example is the increased utilization of the residues from forests and agriculture, which requires safeguards that describe the conditions under which residue can be removed to maintain nutrient balances, soil carbon content and minimize erosion. Furthermore, the increased demand for forest wood and agricultural biomass in general can be expected to stimulate measures to intensify forest and agricultural management whilst mitigating the risk of direct and indirect land use change (LUC). Increased demand for both residues and primary products will need to be managed in a responsible way, which will require the development of appropriate indicators to assess social, economic and environmental sustainability, updated recommendations and education for best management practices for forestry and agronomic production systems, and good governance systems to ensure that supply chains are sustainable.

The most prominent driving forces for modern bioenergy expansion on a global scale are political instruments, agreements, and regulations to reduce reliance on non-renewable, imported fuels and to meet GHG reduction targets. The desire for growth of the bioenergy sector and emergence of bio-refineries is also driven by a number of other factors, including rural economic development and employment, a need for product diversification in the forest and agricultural sectors, the desire to find innovative uses for residue streams and waste products, and efforts to improve the productivity of forests, fields, and degraded lands.

Generally speaking, policy drivers (mandates, renewable portfolio standards) underpinned by financial incentives aimed at renewable energy production and domestic energy security have been more critical in influencing bioenergy expansion at local to global scales than market factors, and as a result, outside of local, small-scale applications, many supply chains are not yet economically viable without external support. Government commitment and support and financial incentives therefore continue to be important for significant, large-scale mobilization of the bioenergy supply chains this project evaluated.

5 OPPORTUNITIES TO SIGNIFICANTLY TRANSFORM BIOENERGY PRODUCTION SYSTEMS

If bioenergy supply chains are to be sustainable over the long term and appeal to a wide range of stakeholders, they must be economically attractive, socially acceptable and offer social and economic benefits to communities, and maintain or improve ecosystem services. In short, they must offer solutions, not problems, for a growing world. In situations where trade-offs between different needs have to be made, stakeholders will have to evaluate and agree on which values are most important in a given context, which trade-offs are considered acceptable, and how systems can be designed to minimize negative consequences while maximizing desired benefits. Sustainability is value driven and time specific.

Critical to supporting the mobilization of sustainable bioenergy supply chains is continued research and development into supply chain optimization, particularly developing more efficient and cost-effective technologies and making use of all of the outputs of bioenergy systems (e.g. including CO_2, ash, lignin, etc.).

Significant opportunities also exist to increase supply chain efficiencies through technology transfer (from regions with well-developed supply chains to regions with minimal bioenergy deployment) and learning-through-doing. Technical learning and putting entrepreneurs to work to increase profits and reduce costs is critical to advancing the efficiency and economic competitiveness of bioenergy systems. Transferring best practices and technologies from more experienced regions while accounting for regional differences, optimizing local conditions, and making use of existing infrastructure can be effective in getting supply chains off the ground. Streamlining biomass supply chains with existing silvicultural and agricultural practices (e.g., timing of operations, use of machinery) to increase efficiencies and cost effectiveness should increase adoption, and can increase the overall productivity of existing practices. Using small-scale niche applications and model farms as a platform for scaling up may be another effective approach to testing and improving supply chain technologies, gaining experience, and increasing stakeholder and investor confidence. Improved financing opportunities for bioenergy would make entry into the market more attainable for smaller firms and enable the development of scalable enterprises such as these.

From an institutional standpoint there are a number of opportunities to not only create a more conducive environment for the mobilization of sustainable bioenergy supply chains but at the same time also improve management of other renewable resources; but leadership needs to be shown.

6 SUPPLY CHAIN SPECIFIC RECOMMENDATIONS FOR MOBILIZATION OF SUSTAINABLE BIOENERGY

6.1 Temperate and Boreal Forests

- The most important driver to increase use of forest biomass for bioenergy is policy-supported price for feedstocks and energy products such as wood pellets.
- There are significant opportunities for further mobilization through enhanced technological and institutional learning; that is, learning-by-searching; learning-by-doing; learning-by-using; learning-by-interacting; and upsizing (or downsizing) a specific technology.
- Trade offers opportunities/incentives for biomass mobilization. Trade can enable the creation or re-establishment of logistic systems that are required for a national mobilization of biomass. The current expansion of the USA wood pellet production capacity, destined for export to the EU, could provide a market and logistical "stepping-stone" to the transition of the USA feedstock supply system that is essential for the scale-up of the USA bio-refining industry.
- One social innovation for increasing supply chain mobilization is the expansion of markets throughout cooperative organization structures, such as: forest biomass supply cooperatives; forest biomass energy firms; and forest biomass trade centers. Support for cooperative organization structures (including items such as the development of professional corps, associations, and formal educational programs) can also be a way to increase the professionalism of the workforce in forest biomass supply chains, which has been identified as one important factor for increased biomass mobilization.
- Integration of energy and forest systems is essential to realize regional to global mobilization potentials. This will require careful attention to the following.
    - Management of biomass quality among stakeholders along the entire supply chain.
    - Integrated planning of bioenergy and conventional wood products sectors.
    - Conversion efficiency and cascading use whereby the forest product value chain is optimized both in added value and in GHG reduction.
    - Integrated forest land planning for energy, conventional wood products and ecosystem services to gain synergies for e.g. forest fire protection, conservation of balanced soil nutrients, biodiversity and water quality.
- Achieving many of the opportunities list above will probably require a culture change in society and certainly in the forest and energy sectors. The following will contribute.
    - Development of a shared vision, and recognition and acceptance of different views and understandings.
    - Development of common sustainability criteria from local to global scales.
    - Development of technical standards for bioenergy products to help remove trade barriers, increase market transparency and increase public acceptance.

Based on the analysis report here, mobilization of forest biomass from boreal and temperate biomes using management systems employed today might provide 5 to 7 EJ year^{-1}. More substantial gains in mobilization to the levels projected by the Renewable Energy Roadmap (Remap) 2030 of the International Renewable Energy Agency (IRENA) and others can only be achieved through an increase in forest management intensity resulting in a substantial increase in the utilisation of forest NPP to mobilize up to 14 to 28 EJ per year (see Table 2.5). Such an increase would require a fundamental shift in the forest and energy systems of many countries. For example, for Canada, reaching a Roundwood-to-NPP ratio of 10% would entail a tripling of the current annual allowable cut (AAC); this would require a fundamental increase in management and utilisation intensity over the current system which is based on extensive forestry, and expansion into currently unmanaged forests. Since forests are publicly owned in Canada, such change would require a public debate.

6.2 Agricultural Crop Residues

This multi-country case study assessed the potential opportunities and barriers to the mobilization of agricultural residues for bioenergy and biorefining in Denmark, the USA and Canada. Collectively, these case studies show that there is a real potential for further development of viable bioenergy and biorefining supply chains based on agricultural residues, if there is political support, best practices are followed for residue removal, and there is continued supply chain development and optimization. Large-scale crop residue removal needs to make economic sense, be environmentally sustainable and be compatible with the agricultural practices in a given area. Future mobilization and sustained establishment of agricultural residue supply chains will be possible if the overall production system satisfies the criteria of diverse clients in the following ways.

- Establish a consistent and stable policy framework that supports bioenergy and products made from renewable biomass and wastes.
- Increase awareness of key stakeholders about the availability of credible, transparent knowledge on processes, costs and sustainability aspects (e.g., for farmers, energy producers and other stakeholders along the supply chain) using a variety of social media and educational and extension programs.
- Develop long-term contracts to increase stakeholder confidence.
- Provide incentives for farmer groups, biomass aggregators and bio-processors to bear the initial investment risk (e.g., subsidies or credits for GHG offsets and energy security enhancements).
- Develop and distribute tools to underpin the confidence of processors of consistent biomass supply addressing how variability will be managed, including quality and storage issues.
- Develop Best Management Practices for a variety of soil types and operating conditions that ensure residue removal is not detrimental to soil health over the long term.
- Develop and agree widely upon credible sustainability guidelines.

IRENA estimates that 13-30 EJ year^{-1} of agricultural residues must be used by 2030 to meet the Sustainable Energy for all (SE4All) target of doubling the share of renewable energy in the global energy mix before 2030 (Nakada et al. 2014). The IPCC special report on renewable energy (Chum et al. 2011) reviewed the vast body of literature on bioenergy resources and reports a technical potential of agricultural residues by 2050 of 15-70 EJ year^{-1}. However, agricultural crop residues are not as good a fuel as forest woody biomass for bioenergy to generate heat and power. These feedstocks are not grown in as high a density as forest biomass, meaning cost of crop residues can be high. The analysis reported here indicates that IRENA and other projections may be possible to achieve with concerted effort at societal levels. The following factors all constitute significant constraints on supply and therefore will need to be overcome or mitigated: world grain market fluctuations; biophysical limitations (e.g., extreme weather events); sustainability considerations (e.g., soil fertility and erosion control); competing uses of residues; distance to processing plants and inefficient transport restricting location of supply regions; uneven distribution of benefits along the entire supply chain from farmers to energy consumers; and lack of incentives for producers to harvest residues.

6.3 Biogas from municipal solid waste (MSW), oil palm residues and co-digestion

This case analyzed biogas production from agricultural and organic residues and considered three potentially significant regional biogas production chains — Municipal Solid Waste (MSW), oil palm residues and co-digestion. Current global MSW production, 1.3 billion tonnes per year, is expected to increase to 2.2 billion tonnes by 2025 (World Bank 2012); about 560 million tonnes is of organic origin; the biogas potential is 48 million Nm^3 or 1.0 EJ. By 2025, 6 billion tonnes of urban waste will contain 1 billion tonnes organic waste with a biogas potential of 86 million Nm^3 (equivalent to 1.8 EJ). Agricultural residues and wastes constitute feedstocks suitable for biogas production. Estimates include: all crop related waste (excl. manure and MSW) amounts to 2.2 billion (10^9 basis) wet (as received) tonnes today and 2.8 billion wet tonnes by 2020; manure amounts to 16 billion wet tonnes today and 18.8 billion wet tonnes by 2020; and straw amounts to 0.8 billion wet tonnes today and 0.9 billion wet tonnes by 2020 (E4Tech 2014). These E4Tech (2013) figures are thought to be on the high side when compared with other studies. However, not all of these residues are accessible and harvesting and logistical costs are relatively high (see also agricultural crop residue chapter), and significant amounts of potential feedstocks mentioned above may already be utilized for other purposes (e.g. energy by direct combustion, producing bio-based products, beneficially recycled on farms). A conservative estimate suggests biogas production in 2020 could generate some 5.3 EJ.

This report identified a number of recommendations essential to improve the mobilization of biogas production. Reliable, long-term financial support (e.g. feed-in tariffs) is especially essential for biogas production based on energy crops; since these crops are produced on agricultural land, production costs can be considerable.

The dependency of biogas production on a constant, reliable flow of high-quality, affordable biomass makes it vulnerable to market disruption and dependent on stable public and political support until a fully competitive business model for feedstocks and energy products emerges.

The following policy recommendations for enhancing biogas development are essential for mobilization potentials to be achieved.

- Inefficiencies, inconsistencies, and intrinsic barriers for biogas production in existing policies need to be identified and removed at local, regional, and national levels.

- Experience indicates consistent policy support is essential, including, where necessary, sufficient economic incentives for investments in AD installations or infrastructure for marketing and utilizing biogas, upgraded gas, and locally- generated electricity.

- Policies that support fossil fuels frustrate development of renewable energy alternatives, hinder new technologies from becoming competitive, and intensify the competition for scarce public funds.

- The public image of biogas production needs to be improved to remove negative perceptions of biogas production, improve supply chain development, and increase community regional support for development of feedstock, gas, and energy markets.

- The general business case for digester performance needs to be improved. Relatively low energy content per unit of feedstock, high initial investment costs, and considerable logistical complexity and cost are formidable barriers to competitive AD systems. As for the other supply chains evaluated in this project, effort must be placed on developing efficient logistical systems, investment in infrastructure, and RD&D to develop advanced hardware and management systems.

- Develop biogas supply and value chains (including access to the grid of many small biogas producers, biogas storage systems) that are integrated with existing residue management systems (e.g., collection of municipal waste, food waste) to improve the competitiveness of biogas production while also garnering public and political support.

6.4 Lignocellulosic Crops In Agricultural Landscapes

Many lignocellulosic crops (e.g. short-rotation willow (*Salix* spp.), the mallee Eucalyptus species native to Australia, switchgrass (*Panicum virgatum*), and poplars (*Populus* spp.) short rotation coppice) that are produced in agriculture-dominated landscapes can produce biomass for energy as well as provide additional ecosystem services and environmental, social, and economic benefits. Positive impacts can be optimized if such systems are carefully designed following consultation with all stakeholders along the supply chain. Their integration into landscapes can help conserve and improve soil quality and reduce eutrophication of aquatic ecosystems, improve habitat heterogeneity in agricultural landscapes, reverse negative biodiversity effects of land abandonment in marginal regions and enhance biocontrol services in agriculture landscapes thus reducing the need for pesticides.

Yet many of the lignocellulosic crop options identified as promising future biomass supply sources are either used very little today, or are used for purposes such as animal feed and pulpwood production. The values of additional ecosystem services can be large but mechanisms for crediting the producer providing them are rarely found and they are often neglected.

This report has identified many opportunities for mobilization of sustainable lignocellulosic crop systems in a range of operational environments. These include the following recommendations.

- Remove policy barriers related to bioenergy in general and lignocellulosic crops in particular that are currently of concern in specific individual countries.
- Anticipate reducing the cost of lignocellulosic bioenergy technologies as production systems mature, and costs fall as operational experience and the scale of production grows. As for forest supply chains, there are significant opportunities for further mobilization through enhanced technological and institutional learning.
- Level the playing field across all energy production systems through concerted public policy discourse.
- The public image of lignocellulosic crops for bioenergy and bio-based product production must be improved. This will require increasing stakeholder confidence and knowledge; available information must be made more widely available through a variety of media; we must broaden the public

discussion of the true costs and benefits of dedicated energy crops so that all stakeholders can be informed by information about all the benefits of the lignocellulosic crops supply chain.

- The promotion of holistic approaches is essential since a narrow focus on biomass production can reduce the value of biomass plantings with regard to the provision of other ecosystem services.

A range of different reports have indicated the potential of lignocellulosic crops as bioenergy feedstock. For example, IRENA estimates that the supply potential of energy crops that must be achieved by 2030 to double the share of renewable energy in the global energy mix is 33-39 EJ per year (Nakada et al. 2014). The IPCC special report on renewable energy (Chum et al. 2011), based on several reports in the literature, gives a much wider range of the technical potential of dedicated biomass production on agricultural land by 2050, stating that it is between 0-700 EJ per year (when also including conventional agricultural crops, with 0 (zero) being the case when no surplus agricultural land will be available due to food sector development). Despite the broad variation in these estimates, which depend on the land availability assumed or on the sustainability issues that need to be satisfied, our report shows that several lignocellulosic crop systems for biomass production for energy can contribute towards fulfilling these potentials. This is further confirmed in the analyses of feedstock cultivation on pastures and grasslands.

6.5 Cultivated Grasslands and Pastures

This case focused on the Brazilian experience, and especially producing sugarcane for ethanol on grasslands and pastureland, since it is an option that could be promoted in several other countries where sugarcane can be cultivated. The project team described sugarcane ethanol production conditions and prospects for expansion, governance, and factors affecting market demand for Brazilian ethanol, including the interaction between the sugar and ethanol markets. Lignocellulosic and other feedstocks were also briefly discussed, especially palm oil biodiesel that has received increased attention in Brazil in recent years. The influences of water resource availability and use were given special attention because of their strong influence on the prospects for bioenergy feedstock production on grasslands and pastures in Brazil and around the world.

This report has found that grasslands and pastures represent a very large resource base on a global level. In Brazil, large-scale mobilization of bioenergy supply chains in Brazil is very possible. Few techno-economic barriers exist and legal conditions for production are settled throughout the country; production systems are mature; and there is technology and capacity to rapidly increase production in response to increasing demand. Progressive infrastructure investments further strengthen capacity, notably in export routes via the Amazon River basin. Brazilian agricultural production can grow without extensive conversion of forests and other native vegetation. Large areas of extensively used pastures are suitable for cultivation of sugarcane and other bioenergy feedstocks, and land productivity improvements in meat and dairy production can accommodate a large expansion of such cultivation. More widespread use of water-efficient irrigation could boost Brazilian agriculture output significantly. The following factors must be understood clearly to enable such mobilization to occur and therefore justify taking action.

- As for other bioenergy options, mobilization can be hampered by uncertainty concerning future markets and evolving regulations. Specifically for the Brazilian sugarcane case, low margins for sugar and ethanol are magnifying the importance of surplus electricity sales to the grid but several barriers inhibit development for electricity co-generation in ethanol mills. Clear and consistent policy definitions and targets providing stable market conditions are required. Policies can either guarantee markets or increase fossil fuels prices sufficiently to make bioenergy options competitive. More favorable conditions for power generators and resource planning integrating bioelectricity with other renewable electricity resources can stimulate development.

- The governance situation in Brazil is illustrative of possible challenges for sustainable mobilization around the world: incentives and alternative regulation (e.g., licences and conditional credits) may be needed to complement governmental command and control to protect native vegetation and promote land use productivity. While consumer demand for sustainable products is increasing, sourcing can be challenging due to diverging views on sustainability aspects, the variety of issues to be considered, and the many suggested indicators for representing these issues. A polarized debate about the priorities of agriculture production versus environmental protection may in itself be a barrier against progress and sensible balancing of these objectives, since debate and conflict contributes to uncertainty about future markets, including sustainability standards and regulations imposed on producers.

- Sustainably increasing food, biomaterials, and bioenergy production on grasslands and pastures requires structural shifts and incentives rewarding higher productivity. This is especially important in cattle production where, historically, ample supply of new land in frontier regions has fostered a culture among cattle producers and associated actors where management options to increase land-use efficiency are less important.

- The analyses showed that productivity improvements in meat and dairy production could release very large grassland and pasture areas for other uses. Illustrative calculations on the global level show that several hundred EJ per year could be produced. Brazilian ethanol production could be many times larger than today. Best management practices for cultivating low productivity pastures will be important since much of the land that can become available through intensification is currently used for extensive grazing. Criteria, data and methods are needed to distinguish highly biodiverse grassland from other land and to address hydrological aspects of grassland and pasture cultivation.

7 GENERALIZED SYNTHESIS OF URGENT OPPORTUNITIES AND RECOMMENDATIONS

The list of barriers to mobilizing sustainable bioenergy supply chains may appear daunting, but fortunately there is an equally long list of corresponding opportunities. The case studies in this report have presented solutions for overcoming barriers to the mobilization of sustainable bioenergy supply chains, and also opportunities for enhancing environmental, social, and economic values through sustainable supply chain development (Figure 1).

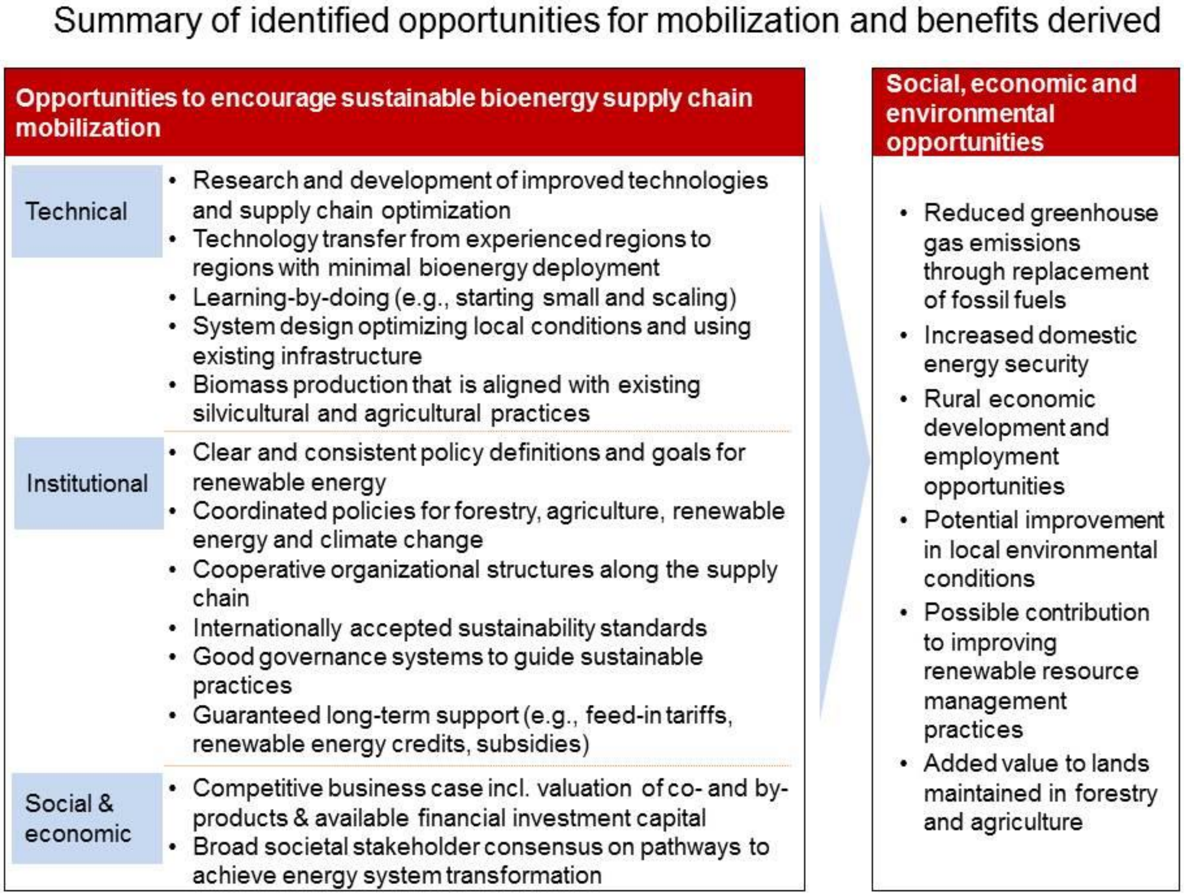
7.1 Solutions for supporting the mobilization of sustainable bioenergy supply chains

Critical to supporting the mobilization of sustainable bioenergy supply chains is continued research and development in supply chain optimization, particularly developing cleaner, more efficient, and more cost-effective technologies. Expanded funding for research programs and demonstration plants would support necessary technological innovation and supply chain optimization.

Significant opportunities also exist to increase supply chain efficiencies through technology transfer (from regions with well-developed supply chains to regions with minimal bioenergy deployment) and learning-through-doing. Technical learning and putting entrepreneurs to work to increase profits and reduce costs is critical to advancing the efficiency and economic competitiveness of bioenergy systems. Transferring best practices and technologies from more experienced regions while accounting for regional differences, optimizing local conditions, and making use of existing infrastructure can be effective in getting supply chains off the ground.

Streamlining biomass supply chains with existing silvicultural and agricultural practices (e.g., timing of operations, use of machinery) is another opportunity to increase efficiencies and cost effectiveness, while at the same time increasing the overall productivity of existing practices.

Using small-scale, niche applications as a platform for scaling up may be another effective approach to testing and improving supply chain technologies, gaining experience and increasing stakeholder and investor confidence. **Improved financing opportunities for bioenergy** would make entry into the market more attainable for smaller firms and enable the development of scalable enterprises such as these.



Summary of identified opportunities for mobilization and benefits derived

Opportunities to encourage sustainable bioenergy supply chain mobilization

Technical
- Research and development of improved technologies and supply chain optimization
- Technology transfer from experienced regions to regions with minimal bioenergy deployment
- Learning-by-doing (e.g., starting small and scaling)
- System design optimizing local conditions and using existing infrastructure
- Biomass production that is aligned with existing silvicultural and agricultural practices

Institutional
- Clear and consistent policy definitions and goals for renewable energy
- Coordinated policies for forestry, agriculture, renewable energy and climate change
- Cooperative organizational structures along the supply chain
- Internationally accepted sustainability standards
- Good governance systems to guide sustainable practices
- Guaranteed long-term support (e.g., feed-in tariffs, renewable energy credits, subsidies)

Social & economic
- Competitive business case incl. valuation of co- and by-products & available financial investment capital
- Broad societal stakeholder consensus on pathways to achieve energy system transformation

Social, economic and environmental opportunities
- Reduced greenhouse gas emissions through replacement of fossil fuels
- Increased domestic energy security
- Rural economic development and employment opportunities
- Potential improvement in local environmental conditions
- Possible contribution to improving renewable resource management practices
- Added value to lands maintained in forestry and agriculture

Figure 1. Summary of opportunities identified to mobilize bioenergy and realize positive benefits in all five supply chains that were evaluated.

From an institutional standpoint there are a number of opportunities to not only create a more conducive environment for the mobilization of sustainable bioenergy supply chains but at the same time also improve management for other renewable resources. These include:

- the development of **internationally accepted sustainability standards** for biomass;
- the creation **of incentives to improve the management of renewable resources in general** (e.g., biomass sustainability standards may lead to a demand for similar standards for other resources and/or may address management issues that have previously been overlooked);
- the **development of a common agenda for agriculture and forestry** that balances demands for traditional products (e.g., food, wood products, fiber), biomass and ecosystem services;
- the **creation of cooperative organizational structures along the supply chain** (biomass suppliers, energy firms and trade centers);
- increased **incentives and regulatory control encouraging better management for land productivity** (e.g., as discussed in Chapter 6, to allow for the production of multiple products without putting additional strain on ecosystem services);
- the **use of decision support systems** integrating biophysical and socio-economic data to guide the sustainable mobilization of biomass, food, and other resources;
- the **coordination of energy, forestry, agriculture and climate change policies** at national and multi-national levels;
- the **creation of common, clear and consistent definitions** related to renewable energy and climate change;
- the provision **of long-term guaranteed financial support (e.g., feed-in tariffs, subsidies, renewable energy credits, etc.)** for emerging businesses; and
- **government support for research and development programs**.

7.2 Potential environmental, social, and economic benefits of sustainable bioenergy production

With careful planning and management, sustainable bioenergy supply chains can provide a number of opportunities to improve on social, economic, and environmental values. These include:

- reducing greenhouse gas emissions through the replacement of fossil fuels;
- increasing domestic energy security;
- adding value to existing silvicultural and agricultural practices;
- boosting rural economies;
- creating job opportunities;
- improving biodiversity, soil productivity and/or hydrological conditions (e.g., where carefully designed lignocellulosic crops replace or complement annual cropping systems; better waste

management opportunities through biogas production; adding value to lands kept in forests or agriculture; etc.);

- encouraging dialogue on sustainable land use management for multiple products, including the development of sustainability criteria and indicators and efforts to assess the efficacy of governance systems for renewable resource management; and

- inspiring technological innovation in forestry, agriculture, and waste management.

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1

INTRODUCTION

1.1 Background

Significant opportunities exist to reduce greenhouse gas emissions, increase domestic energy security, boost rural economies, and in some cases even improve local environmental conditions through the deployment of sustainable bioenergy and bio-based product supply chains. There are currently a wide selection of possible feedstocks, a variety of conversion routes, and a number of different end products that can be produced on a range of scales. These include, among others liquid and gaseous fuels, heat energy, electricity, biogas, food and feed ingredients, chemicals, and materials (e.g., biobased plastics).

There are, however, a number of technical, institutional, and socio-economic barriers to market penetration of bioenergy that will need to be overcome in order to realize opportunities on a wider scale. Some of the most significant barriers include issues related to

- supply chain complexity and cost, including logistics and intermediate storage;
- market development and penetration;
- confidence in feedstock inventory estimates;
- development status of major conversion technologies; and
- meeting a growing number of sustainability requirements.

Biomass supply chains and conversion technologies are in various stages of commercial readiness and exhibit various levels of complexity, therefore the applicability and extent of the barriers to deployment of bioenergy will vary from supply chain to supply chain. Understanding the various feedstocks and sustainable conversion pathways leading to biofuels, bioenergy, and co-produced bio-based products is crucial to overcoming these barriers and developing an effective business case for emerging industries. Energy market penetration will also depend heavily on an area’s existing energy profile, rate of energy technology development (outside of bioenergy), and development of government targets and incentives to promote renewable energy, such as those in the EU Renewable Energy Directive of 2009 (European Commission 2009).

In some countries such as Denmark, Finland, and Sweden, conditions have favored bioenergy for years, and biomass is already widely used to generate heat and power. In other countries, deployment remains minimal despite an abundance of available biomass resources. In Canada, for example, there is a complex scenario at play in which both rich forest resources and substantial fossil fuel reserves are driving the economic engine. There and in other countries recent years have seen economic downturns, significant setbacks of the forestry sector, and annual harvests much lower than the annual allowable cut (Canadian Council of Forest Ministers 2008). Substantial areas of agricultural land, including pastures, have been set aside or are under-utilized. These examples indicate the potential for increased use of biomass resources that could be mobilized for bioenergy production. Adding biomass to the current basket of forest and agricultural products could regenerate flagging industries and achieve other goals; however, adoption and development tend to be slow where fossil fuels are abundant, renewable energy goals are not clearly defined, and existing business models do not contribute to competitiveness.

One of the major challenges to realizing mobilisation potential is that biomass supply infrastructure has not yet been fully established in many parts of the world. For example, in a few countries such as Sweden and Finland, the use of forest wood for energy is a substantial activity that has helped to shape the wood supply infrastructure so that it can now handle wood for biofuel relatively efficiently. In most countries, however, biomass supply infrastructure has yet to be developed in response to changing demand patterns (De Jong 2012). Efficient and commercially viable conversion technologies are also lacking for a number of supply chains and regions. Furthermore, the willingness of stakeholders to invest in infrastructure and technology is eroded by uncertainties about long-term feedstock supply of both crops and value chain residues. In Canada, for example, studies have shown huge variations in supply estimates (Wood and Layzell 2003, Smith et al. 2009, Dymond et al. 2010, Kennedy et al. 2011). This variability is due to operational, sustainability, and conversion constraints acting along complex supply chains, and we need to understand these constraints better in order to develop a realistic resource assessment.

Barriers to mobilizing bioenergy supply chains are not only present in technology and the economics of logistical systems, but also in institutional development. Policies need to be coordinated across departments (e.g., forestry, agriculture, energy, environment, and climate change) to support and govern emerging bioenergy systems. Regulations must ensure that increased biomass outputs respect sustainability considerations, which also need to be better understood. One example is the increased utilization of the residues from forests and agriculture, which can require regulation and measures to maintain nutrient balances and minimize erosion. Furthermore, the increased demand for forest wood and agricultural biomass in general can be expected to stimulate measures to intensify forest and agricultural management and potentially contribute to land use change. These increased demands for both residues and primary products will need to be managed in a responsible way, which will require the development of appropriate indicators to assess socioeconomic and environmental sustainability, updated recommendations on silviculture and agronomic management, and good governance systems to ensure that supply chains are sustainable.

To summarize, challenges in mobilizing sustainable bioenergy supply chains include the following.

1. Developing competitive feedstock supply and value chains, based on the identification of appropriate feedstock and conversion technologies, including co-produced bio-based products and their substitution for alternative products.

2. Understanding constraints on feedstock availability and cost competitiveness, including operational level considerations and the adoption of techniques for mitigating sustainability risk.

3. Quantifying positive and negative environmental and socioeconomic consequences of different bioenergy supply chains, including benefits of co-products.

4. Developing governance systems for sustainable supply chains that provide sound operating conditions for actors along the supply chains while addressing concerns about various risks associated with bioenergy. As feedstock production is geography-dependent, site-specific issues need to be reconciled within the context of global supply chains.

1.2 AIM

The concerns outlined above indicate the need for a comprehensive understanding of the many elements involved in bioenergy mobilization in order to create a truly sustainable economic business case for bioenergy within the bio-economy framework. This report brings together expertise from six IEA Bioenergy Task – Tasks 37 (Energy from Biogas), 38 (Climate Change Effects of Biomass and Bioenergy Systems), 39 (Commercialising Conventional and Advanced Liquid Biofuels from Biomass), 40 (Sustainable International Bioenergy Trade: Securing Supply and Demand), 42 (Biorefining – Sustainable Processing of Biomass into a Spectrum of Marketable Bio-based Products and Bioenergy), and 43 (Biomass Feedstocks for Energy Markets) – to analyze a range of supply chains, address the issues outlined above, and come up with innovative ways to overcome barriers and enhance the mobilisation of bioenergy supply chains that are commercially competitive and are sustainable according to international standards.

1.3 SCOPE AND METHODOLOGY

This report distills and synthesizes a wider body of work produced as part of a multi-year IEA Bioenergy inter-Task collaboration involving researchers from the six participating Tasks. The purpose of the collaboration has been to identify sustainable biomass systems and promote their mobilisation through a series of case studies. Combining their own areas of expertise, researchers have developed a framework for analyzing case studies that includes aspects of feedstock availability, applicable conversion processes, supply chain integration, greenhouse gas balances, land use issues, governance mechanisms, and other aspects of bioenergy production and supply.

The work was accomplished by dividing research areas among different working groups (shown in Figure 1.1), taking a global perspective to describe relevant forest, agricultural, and dedicated-energy-crop supply chains but choosing case studies that generally fall within the expertise of the Tasks involved. The case studies analyzed in this project were selected from supply chains representing major global biomes and potential residue supplies:

- Forest biomass from temperate and boreal ecosystems
- Agricultural residues in the Danish, Canadian and USA context
- Biogas production from municipal wastes and agricultural residues
- Lignocellulosic crops
- Cultivated pastures and grasslands in Brazil

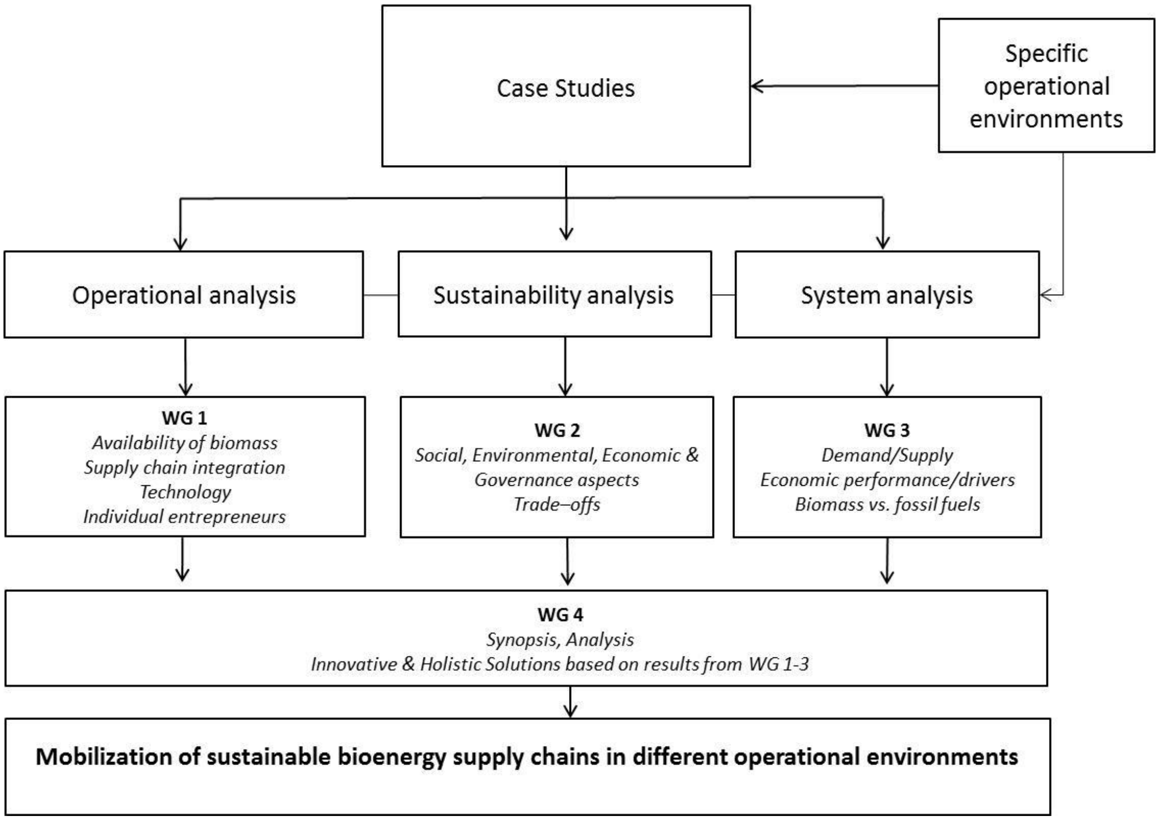


Figure 1.1. Overview of project structure.

The case study analyses in chapters 2 through 6 are structured around the elements shown in Figure 1.1. Each supply chain was analyzed in terms of

- feedstock availability estimates, including operational level considerations;
- the current state of technology, supply chain integration, and market penetration;
- sustainability aspects and governance systems;
- barriers to mobilisation; and
- opportunities to overcome barriers and enhance sustainable supply chain mobilisation.

Chapter 7 provides a synthesis of the most critical take-home messages from the various case studies, lifting lessons-learned from specific cases into the wider context of mobilizing sustainable bioenergy systems.

1.4 SUSTAINABILITY ASSESSMENT OF CASE STUDIES

In order to be sustainable, bioenergy supply chains must be environmentally, economically and socially viable over both the short and long terms. Many groups have proposed indicators to evaluate the sustainability of supply chains but there is currently no internationally accepted framework for assessment. In an effort to distill the indicators that are most practical and useful for decision makers from the plethora available, a team at Oak Ridge National Laboratory has selected a set of key indicators of bioenergy sustainability and proposed a method for their application to a bioenergy supply chain from feedstock production through energy product consumption (Dale et al. 2013). Thirty-five indicators under 12 categories are used to indicate the environmental and socioeconomic values that should be assessed across the entire supply chain.

Figure 1.2 illustrates the application of this assessment method to the supply chain for liquid biofuels, showing the six categories of environmental indicators (soil quality, water quality and quantity, greenhouse gases, biodiversity, air quality, and productivity), and six categories of socioeconomic indicators (profitability, social well-being, external trade, resource conservation, and social acceptability). The diagram shows which indicators, according to the assessment, are correlated with major effects for each element of the supply chain. While this approach was developed for liquid biofuels, it is also applicable to bioenergy.

This approach provides a basis for comparing changes in sustainability over time for a specific bioenergy pathway or for comparing across pathways. It is also a means to quantify and evaluate the sustainability of bioenergy supply chains across different regions and production systems. Because of its practical nature and applicability to a wide range of systems in different regions of the world, it has been used as the basis of the sustainability discussions for a number of the case studies analyzed in this report.

Other case studies in this analysis discuss the various sustainability story lines that could emerge depending on the scale of mobilization and the state of governance systems in place (Figure 1.3). (This methodology is discussed further in Chapter 7.) Both frameworks offer useful approaches for assessing complex systems.

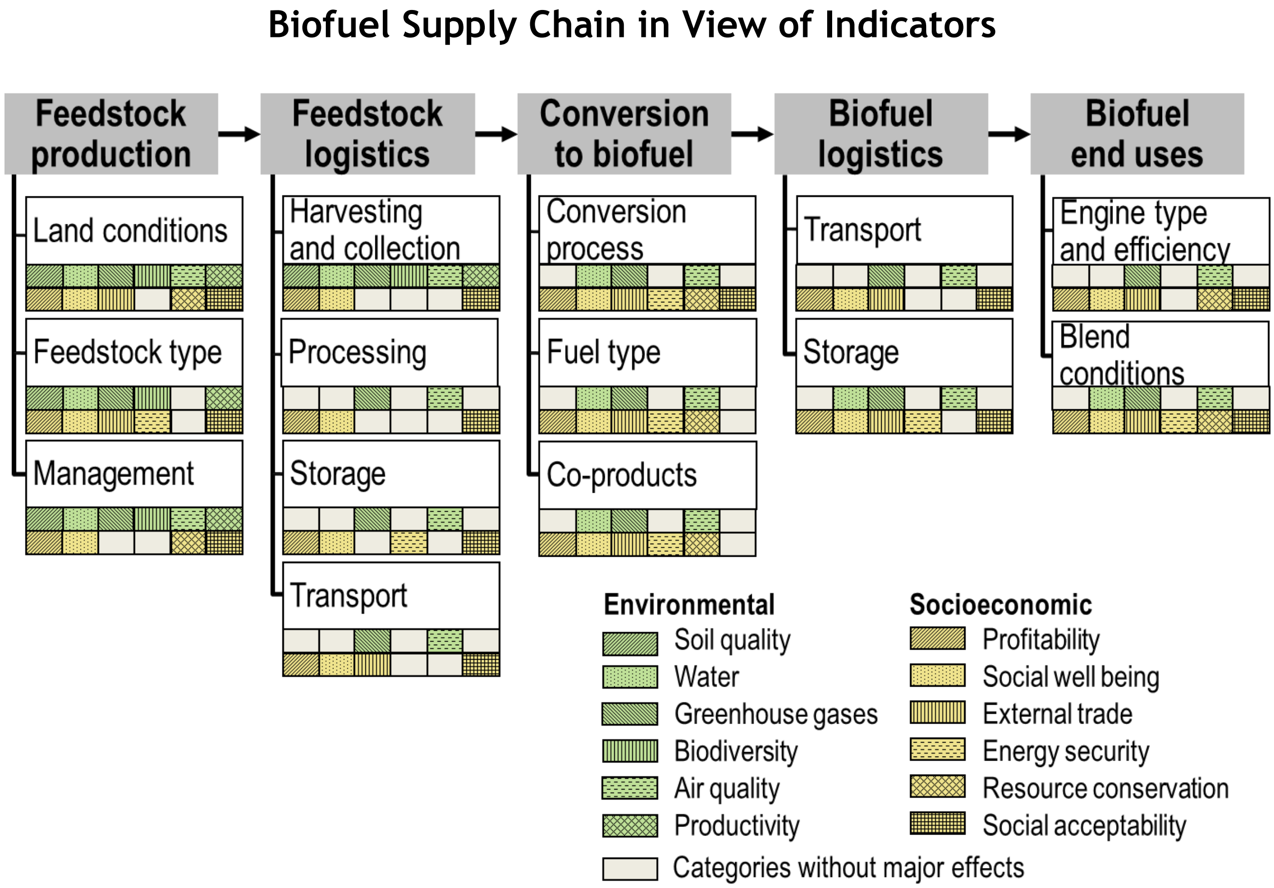
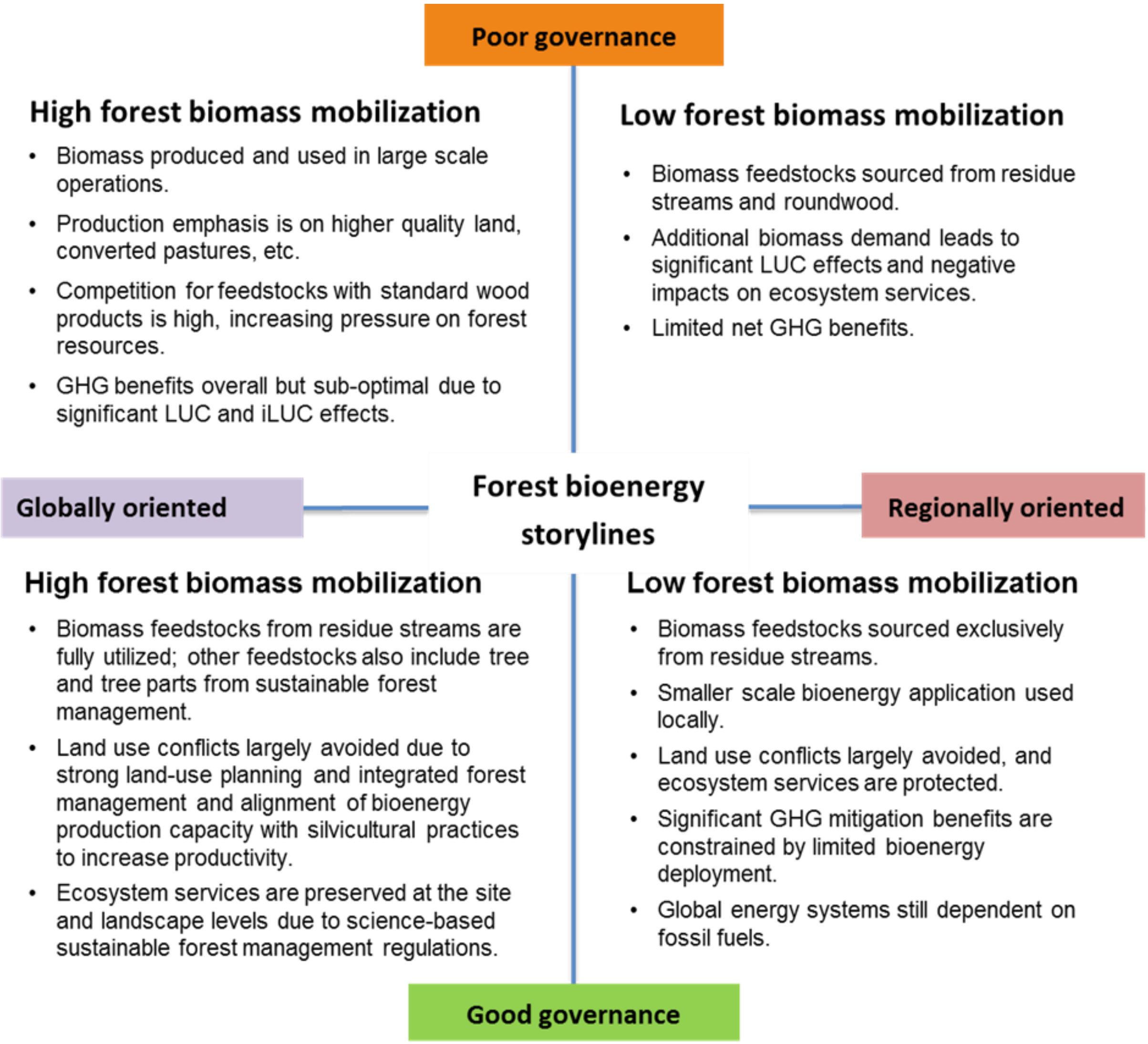


Figure 1.2*. Stages of the biofuel supply chain, elements within those stages, and categories of environmental and socioeconomic indicators of sustainability that represent major effects for each element (Dale et al. 2013). Under each element of the supply chain, the top row of symbols show which categories of environmental indicators (green) have a major effect, and the second row shows categories of socioeconomic (yellow) indicators having a major effect on the element.*



High forest biomass mobilization

- Biomass produced and used in large scale operations.
- Production emphasis is on higher quality land, converted pastures, etc.
- Competition for feedstocks with standard wood products is high, increasing pressure on forest resources.
- GHG benefits overall but sub-optimal due to significant LUC and iLUC effects.

Low forest biomass mobilization

- Biomass feedstocks sourced from residue streams and roundwood.
- Additional biomass demand leads to significant LUC effects and negative impacts on ecosystem services.
- Limited net GHG benefits.

High forest biomass mobilization

- Biomass feedstocks from residue streams are fully utilized; other feedstocks also include tree and tree parts from sustainable forest management.
- Land use conflicts largely avoided due to strong land-use planning and integrated forest management and alignment of bioenergy production capacity with silvicultural practices to increase productivity.
- Ecosystem services are preserved at the site and landscape levels due to science-based sustainable forest management regulations.

Low forest biomass mobilization

- Biomass feedstocks sourced exclusively from residue streams.
- Smaller scale bioenergy application used locally.
- Land use conflicts largely avoided, and ecosystem services are protected.
- Significant GHG mitigation benefits are constrained by limited bioenergy deployment.
- Global energy systems still dependent on fossil fuels.

Figure 1.3. Possible bioenergy scenarios based on scale of biomass utilization and presence or absence of good governance based on a forestry example (adapted from Chum et al. 2011).

Chapter 7, *Integration, Synthesis, Conclusions, And Recommendations*, briefly synthesizes the rich detail provided by the case study analyses in chapters 2 through 6, extracting the main take-home messages that appeared again and again across case studies, and scaling these findings up to the wider context.

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2

BOREAL AND TEMPERATE FOREST SUPPLY CHAIN

2.1 INTRODUCTION

Globally, wood already plays a major role in energy provision, with 1.9 x 10^9 m^3 or 55% of global wood use being directly employed in energy production annually, largely through traditional use in developing countries (FAO 2014). Moreover, of the 1.7 x 10^9 m^3 of industrial roundwood used each year for production of conventional wood products (such as sawnwood, pulp, fiberboard), 40% ends up in energy production through the burning of by-products such as sawdust, bark and black liquor (Hakkila and Parikka 2002). It is estimated that 36.2 EJ of the world's energy production comes from forests: approximately 30 EJ from traditional fuelwood, 3 EJ from charcoal production, and the remainder as modern biomass use (Sims et al. 2007).

Although definitions differ in the literature, forest biomass supply can be defined as 1) the current production of roundwood for conventional wood products (e.g. sawnwood, pulp and paper, panel), 2) the potential stem wood that could be additionally harvested within the sustainable harvest limit, 3) primary forestry residues, e.g., logging residues, early thinnings and 4) secondary forestry residues, residues from the industrial processing of wood.

With their generally mature forestry sectors, countries from the boreal and temperate biomes (Figure 2.1) in Europe, North America and some parts of Oceania are expected to play an important role in the mobilization of forest biomass for energy. In these countries, production models are mostly based on long-rotation forestry (Egnell and Björheden 2013), which presents unique challenges and opportunities relative to tropical and sub-tropical forestry models or short-rotation forestry. Wide differences exist between temperate and boreal countries with regard to their current level of forest biomass mobilization, and challenges and opportunities for the enhanced mobilization of forest biomass supply chains will differ significantly from country to country.

2.2 ANALYSIS

2.2.1 Factors affecting market demand

2.2.1.1 Economic and political drivers for energy and feedstock production

The development of forest bioenergy is motivated in large part by political agendas, primarily those pertaining to renewable energy and climate change. Government programs have been created in Europe and North America to support the development and commercialization of bioenergy technologies, including forest-based bioenergy.

In addition to policy drivers, forest bioenergy programs have been developed in a number of regions as a means to diversify the forest products industry, add value to existing forest operations, enhance rural economies, and improve forest health (e.g., through thinning operations). These factors are especially important in light of the post-2008 downturn in the pulp and paper and furniture industries in some countries, for example Canada and the United States.

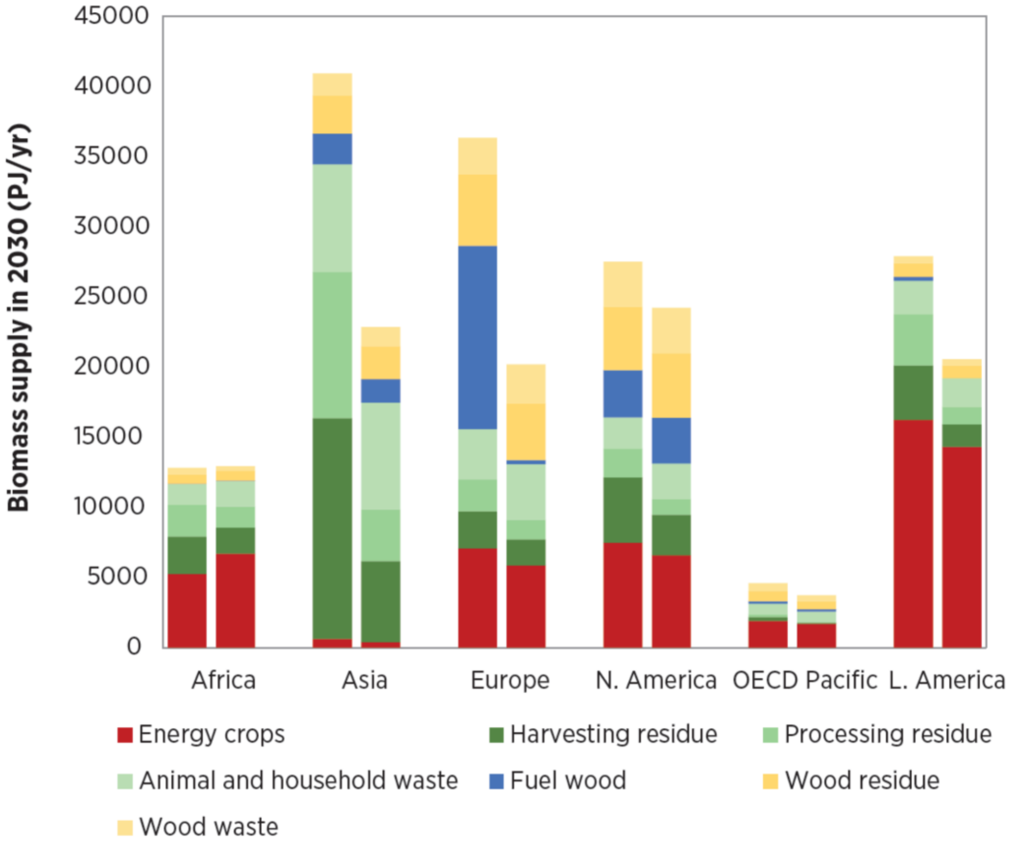


Figure 2.1. Breakdown of biomass supply by source and regions in the REmap 2030 (IRENA 2014). Biomass from forestry is included in the fuel wood, wood residue, and wood waste categories. Russia is included in Europe. The first and second bars for each world region refer to high and low estimates, respectively, with the low estimate applying severe environmental restrictions and assuming only the utilization of forest resources currently under commercial operation to avoid a negative impact on biodiversity by developing forest plantation in pristine (i.e., non-disturbed) areas.

2.2.1.2 Overview of existing and potential markets

Forest biomass is primarily consumed locally due to its low energy density and high transportation costs. From the 1930s until present time the primary energy use for forest biomass in boreal and temperate regions has been for heat and CHP production integrated with existing industries, mainly the forest industry. This market is only likely to increase by 1% of total bioenergy demand by 2020 (from 15%-16%) thereby having only a marginal impact on biomass mobilization.

Power production in stand-alone facilities is expected to show the largest increase of all forms of biomass energy, from about 4.8 EJ in 2010 to 17.3 EJ in 2035. Biomass-powered heating services for buildings are expected to increase from 3.7 EJ to 6.3 EJ over this same time period. These assumptions are driven by an expected increase in the combustion of biomass in CHP facilities and co-firing with coal to help meet renewable energy and GHG mitigation targets (IEA 2013). In temperate and boreal regions, a significant proportion of biomass used in these applications will come from forests.

A number of countries without significant forest resources are also expected to derive a growing percentage of renewable energy from forest biomass through the import of wood pellets from producing countries. The main driver for global trade in woody biomass from boreal and temperate forests is primarily linked to policy targets and supply costs. Demand regions could technically supply sufficient biomass for domestic supply, including the EU (Lamers et al. 2014). Nevertheless, in a global competitive setting, internationally traded woody biomass is often cheaper and thus preferred over more expensive local biomass. The total demand for wood pellets in heat and power production by 2020 would equal 32-36 Mtonnes (Figure 2.2) about twice as much as in 2010.

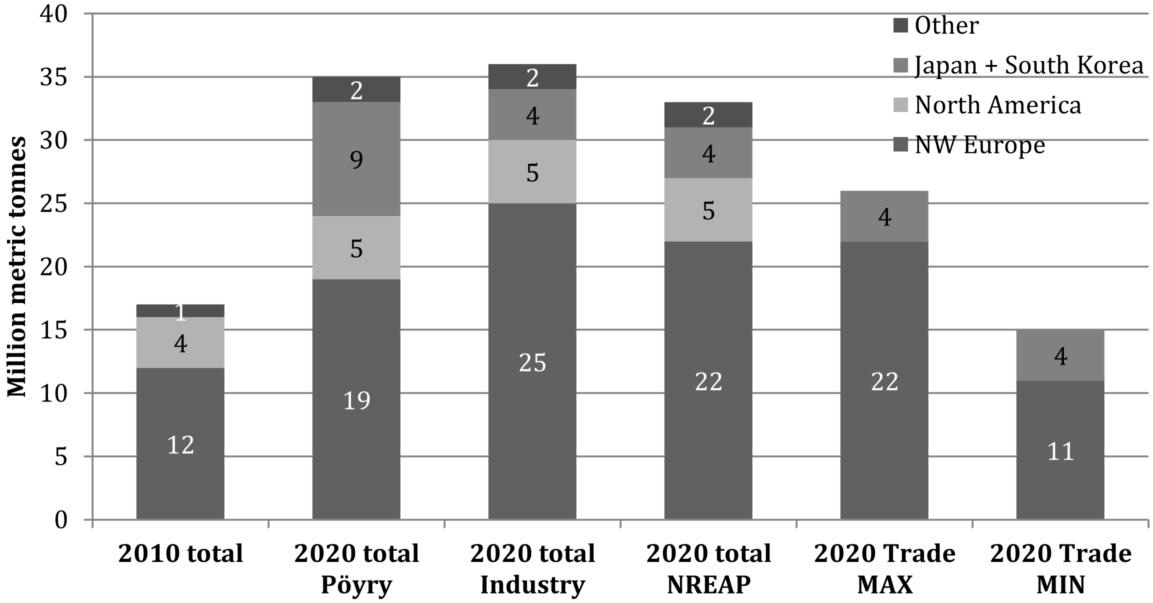


Figure 2.2. Estimated woody biomass demand for large-scale heat and power generation by 2020. Note: NW Europe includes Belgium, Denmark, the Netherlands and the UK; Japan and South Korea demand is only for extra-SE Asian supply. Estimations are based on industry and NREAP projections for NW Europe and calculations by Pöyry (2014). MAX and MIN refer to maximum and minimum estimates of trade.

The USA and Canada are assumed to satisfy domestic demand regionally due to their low supply costs. Japan and South Korea are assumed to import 4 Mtonnes by 2020, with South Korea sourcing mostly from other Asian countries. Other world regions may require as much as 2 Mtonnes. The single largest uncertainty factor regarding tradable woody biomass demand by 2020 is the domestic supply within the EU. So far, NW Europe has been predominantly import oriented. By 2020, a larger fraction could be supplied from within the EU (e.g. the Baltic States).

The majority (80%) of EU demand is satisfied by trade within the EU (see Figure 2.3 for a map of wood pellet flows to EU countries). In 2010, 4.1 Mt of wood pellets were traded among EU states. In the same year, 2.6 Mt were imported from countries outside the EU, primarily Canada (0.9 Mt) and the USA (0.4 Mt) (Sikkema et al. 2011, Goh et al. 2013). Cheaper shipping and handling costs in the Southeast USA are currently challenging western Canada's position as the largest exporter of wood pellets to the EU. However, increased demand for pellets in Japan and South Korea may create new markets for pellets from Western Canada in the coming years (Goh et al. 2013).

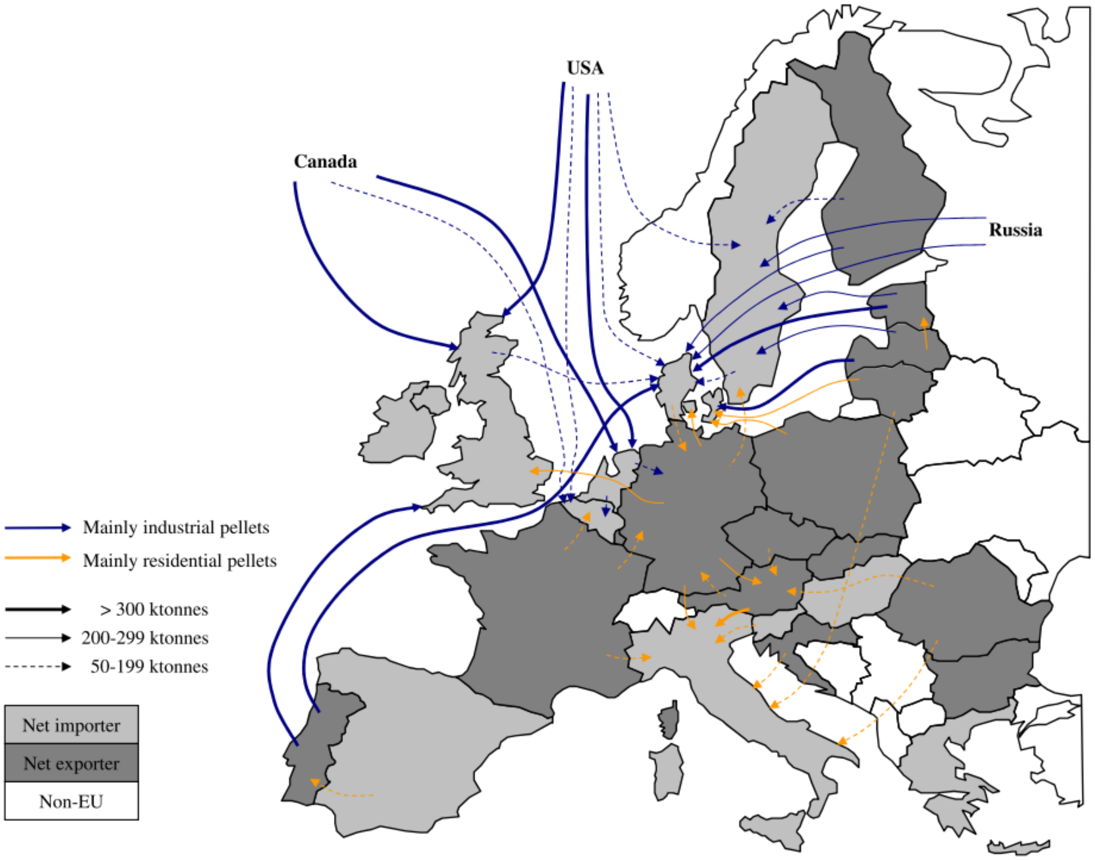


Figure 2.3. Annual wood pellet trade flows into and within the EU between 2010 and 2013.

The global demand for traded wood pellets from boreal and temperate forests to generate heat and power is expected to reach 15-26 Mtonnes (264-458 PJ) by 2020. The EU and to a lesser extent Asia (South Korea and Japan) will likely remain the key demand regions. Within Europe, the UK, the Netherlands, Belgium, Denmark and Sweden are expected to remain net importers at least until 2020 (Kranzl et al. 2014). For a closer look at markets and production in a selection of key regions, see Table 2.1.

Table 2.1. Summary of bioenergy production in select countries.

Country	Primary drivers	Domestic bioenergy use	Capacity and infrastructure	Exports
Finland	1970s oil crisis and energy security (original driver) EU renewable energy and GHG emissions targets Forest economy and rural employment	24% of final energy consumption in 2013 Consumed 42 million m^3 wood for energy in 2013 (Statistics-Finland 2014)	Third highest capacity for biomass power generation in EU after Germany and Sweden Dominated by co-generation facilities in 2-20 MW_e range CHP facilities are a mixture of stand-alone and integrated into industry Widespread district heating grids – 50% of total heat comes from district heating	Export country for the European market, primarily exporting to Sweden but also Denmark, the UK and Belgium
Sweden	Same as Finland, above	34% of total energy consumption in 2013, the highest in any OECD country (SVEBIO 2013) 130.2 TWh (SVEBIO 2013) 90% of feedstock comes from forests Forest-derived transportation fuels on the market since 2011 with an annual capacity of 1 million litres (Holmgren 2012)	District heating is hugely influential, heating 93% of apartments and 83% of commercial spaces (SEA 2013) Transitioning towards more efficient CHP with support from Green Electricity Certificates (Westholm and Lindahl 2012)) Industry still most prominent market, accounting for 24% of total energy use in the country, 42% (0.22 EJ) of which is derived from biomass including black liquor and other pulp and sawmill residues (SEA 2013) Significant research and development into converting forest biomass into transportation fuels (SEA 2013)	Sweden is a net importer of wood pellets.

Country	Primary drivers	Domestic bioenergy use	Capacity and infrastructure	Exports
USA	Domestic energy security National GHG reduction goals Rural economic development	Bioenergy is the largest national source of renewable energy (48% of total renewables or 4.6 EJ in 2011) Total solid biomass used for bioenergy purposes was around 2 EJ between 2002 and 2013 (IEA 2014) Industry still the largest user	Most residues come from privately owned forests in the South District heating and CHP not likely on a large scale due to a lack of district heating infrastructure Relatively large network of pellet mills oriented towards processing residues for export Leader in cellulosic ethanol research and development (though largely with a focus on agricultural residues)	Major exporter of wood pellets to Europe Large share of exports go to the UK
Canada	Forest industry diversification and rural economic development	Only accounted for 0.52 EJ in 2011, primarily industrial wood waste and spent pulping liquors (400 PJ) with the remaining used in traditional combustion for residential heating, district heating and CHP Bioenergy use has been declining in Canada, from 0.58 EJ in 2007 to 0.52 EJ in 2011	District heating and CHP production in stand-alone facilities currently limited but with great potential Installed capacity of co-generation facilities was 466 MW_e and 20 MW_{th} in 2012 while heat-only facilities had an installed capacity of 75.5 MW_{th} Efforts in small communities have resulted in the rapid expansion of district heating capacity; in 2012 12 more district heating facilities were under construction with a total installed capacity of 43.9 MW_{th} Installed wood pellet production capacity of 3.22 Mtonnes, operating at 65% total capacity (Bradley and Bradburn 2012)	Major exporter of wood pellets to global market 90% of exports go to Europe Canadian exports grew from 1.3 to 1.6 million tons annually from 2012 to 2013 as European, North American, and Asian demands increased (Statistics-Canada 2014) Growing wood pellet production capacity in the USA threatening to compete with Canadian exports to Europe Renewable energy targets in Asia, primarily South Korea and Japan, may make these favourable markets for future export

Industry continues to be the largest consumer of biomass for energy in major demand regions (Table 2.2). Although still very significant, this sector is not expected to experience much growth in the coming years.

Table 2.2. Industry share of bioenergy for select countries.

Country	Industry share of bioenergy demand
US	• 60% of all wood and waste biomass for bioenergy was consumed by industry in 2009, primarily in Kraft pulp mills (EIA 2012).
Canada	• The pulp and paper sector continues to be the single largest contributor to Canadian bioenergy, accounting for >50% of the industrial use of biomass (NEB 2014). • 39 facilities are currently operating onsite co-generation facilities.
Finland	• The wood products and manufacturing sector is the single largest producer and consumer of bioenergy, accounting for ~70% of all bioenergy production in 2010 (Aslani et al. 2013). • Combustion of black liquor for chemical recovery in Kraft pulp mills is the dominant biomass energy source.
Sweden	• Industry demand represented 50% of total bioenergy demand in 2010. • Of industry’s total energy demand of approximately 0.53 EJ, 0.22 EJ was met by biomass, including black liquor, other pulp residues and sawmill residues. • The pulp and paper sector remains the largest consumer, accounting for 52% of total industrial demand in 2010 and 90% of industrial bioenergy use (0.18 EJ excluding biomass based electricity from the grid) (SEA 2013).

2.2.2 Supply

Lauri et al. (2014) developed global supply-cost curves for woody biomass for the year 2050 (the target year in IEA Blue Map (IEA 2010)). According to those curves (Figure 2.4), with low energy wood prices (< 5 US$/GJ, i.e., < 36 US$/m^3) the most important feedstock source for bioenergy production in the world in general, and in the temperate and boreal biomes in particular, is likely to be forest industrial by-products from wood processing (e.g., bark, black liquor, sawdust, sawchips; orange portions of the curves). This is already the case today, because they are the cheapest and most accessible feedstock source. When energy wood prices exceed 5 US$/GJ, logging residues (dark blue portions of the curves), non-commercial roundwood (green portions) and plantations (aqua portions) are predicted to begin to replace forest industry by-products as the most important source of energy wood. When energy wood prices exceed 10$/GJ (72$/m3) the diversion of industrial roundwood (dark red and clear blue portions of the curves) towards energy production rather than material conventional wood products (i.e. sawnwood, pulp and paper, fiberboard) starts to increase (Figure 2.4). However, the elasticity between demand and supply might vary quite much at the regional level; for example, in regions where the actual forest harvesting rates are much lower than the annual available cut (AAC), as is the case in some provinces of Canada, the response to price might yield a different pattern.

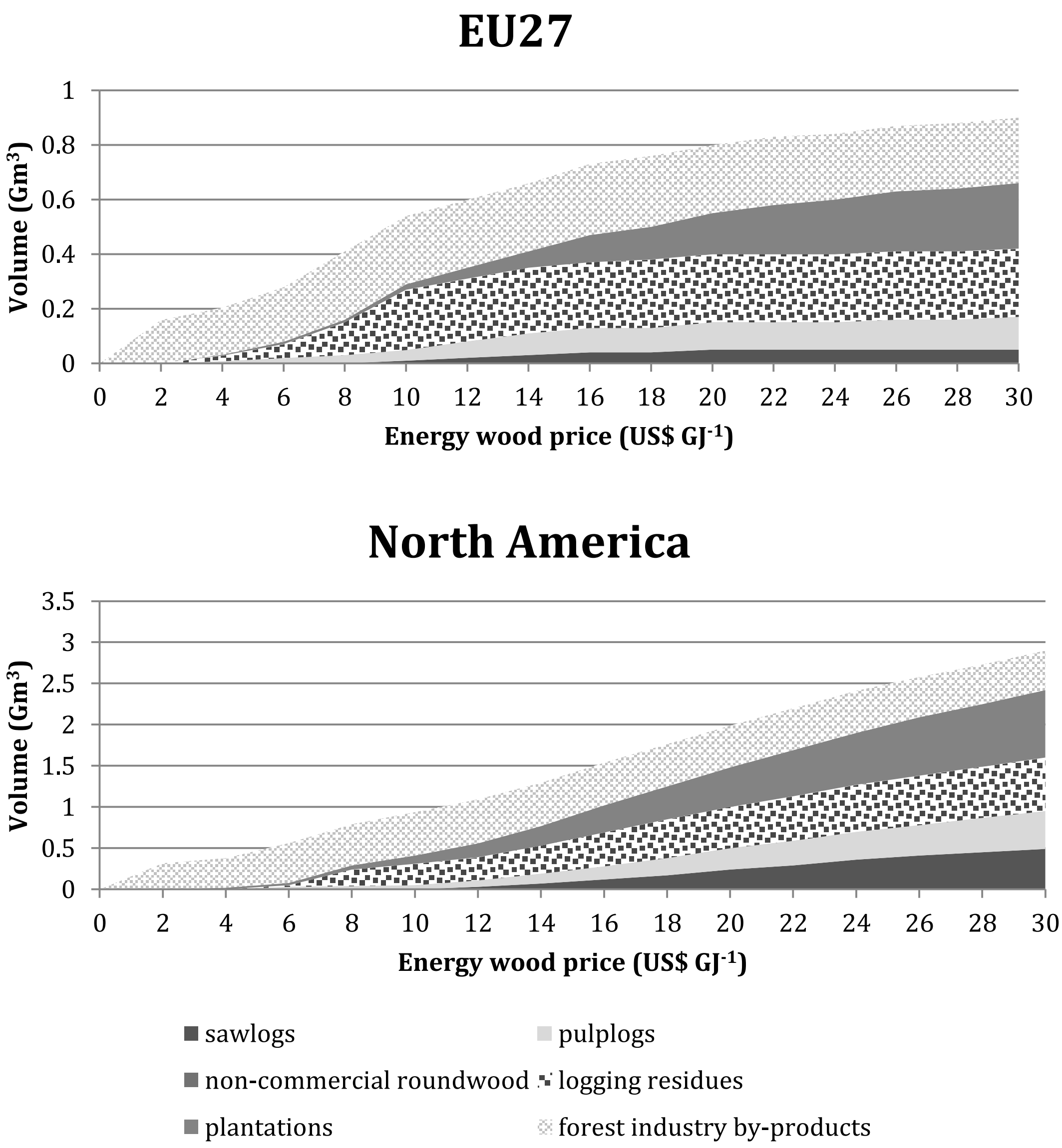


Figure 2.4. Wood fiber uses in 2050 at different hypothetical energy wood prices. The units of x-axis are US$/GJ . From Lauri et al. (2014). Note : "Pulp logs" also include other industrial roundwood. Forest industry by-products include bark, black liquor, sawdust, sawchips, and recycled wood. Logging residues consist of harvest losses, branches and stumps and are by-products of roundwood harvesting. Harvest losses are stemwood that is unsuitable for industrial roundwood because of unwanted stemwood sizes. Non-commercial roundwood is composed of roundwood of unwanted species. The EU27 includes European Union, Russia includes Russia and rest of Europe, and North America includes Canada and USA.

Energy wood prices affect fiber use for conventional wood material products through two opposite processes: on the one hand, the 'by-product effect' increases wood fiber use for conventional wood products when energy wood prices are higher because of the profitable outlet for energy for the industrial by-products produced by wood processing. On the other hand, the competition effect decreases fiber use for material products when energy wood prices are higher because both material products and energy compete for the same feedstock resources (Lauri et al. 2014). At the global level, the by-product effect dominates when prices are lower, but the competition effect becomes stronger when industrial roundwood start to be diverted to energy production when prices increases above 10$/GJ (Lauri et al. 2014). At this price, the intensification of forest management also increases, and the amount of unmanaged forests being converted to management rises, with the highest pressure being seen in the European Union (Lauri et al. 2014). It is therefore at this price threshold that strong environmental governance aimed at ensuring the most benefits in terms of GHG emissions and protecting ecosystem services become all the more crucial (see section D).

According to data in Raunikar et al. (2010), industrial roundwood prices have stayed close to or below 100 US$/m^3 (in real US$ of 1997) and energy wood prices around 50 US$/m^3 (6.90 US$/GJ) for most of the last 50 years. An energy wood price reaching the threshold of 72 US$/m^3 (10 US$/GJ) is plausible. An energy wood price increase of up to 216 US$/m^3 (30 US$/GJ) as modelled in Lauri et al. (2014) due to increased demand for energy wood would imply a significant structural change for the forest sector and/or to forest land base. However, current global coal prices are around 3 US$/GJ and they are expected to stay more or less constant at least for the future (e.g. EIU-GFS (2015)) it is difficult to imagine the energy sector would pay significantly more for woody biomass when they could use coal instead. Bioenergy from woody biomass would therefore require either large subsidies, or high taxes for fossil fuels (Lauri et al. 2014).

2.2.3 Economic competitiveness relative to reference energy production systems

Use of wood for energy is often considered much more expensive than generating energy from fossil fuels, such as coal or oil (Mann 2004). In fact, a study by Hughes (2000) found that in most cases, the cost differential between biomass and coal is not sufficient to generate a profit, especially when operating and maintenance costs are included in the equation. This is what drives the bioenergy sector’s reliance on cheap residues from milling operations (Tan et al. 2008). Therefore, policies rather than competitive advantages are driving the current development and use of wood-based bioenergy systems. Numerous policy-based drivers such as climate change mitigation, energy security, greenhouse gas reduction targets, rural employment, etc., have all influenced government support for bioenergy and biofuels (Hultman et al. 2012). Approaches to encourage production and use vary widely by jurisdiction and are a product of each government’s policies, programs and underlying political drivers.

If wood-based bioenergy is to become cost competitive with current coal prices, feedstock procurement, conversion technologies and other supply chain systems will require significant research, development and optimization. The exceptions to this are Nordic countries, where systems are already optimized to a level of economic competitiveness.

Woody biomass is most competitive when it is a by-product of the forest industry. Black liquor, bark and sawdust from mills have been very competitive across the EU and North America over several decades. In fact, costs are often negative at the production facility because if these byproducts are not used for energy then waste handling charges will be incurred to dispose of them. While the cost of transporting mill residues is relatively small, the costs associated with harvest residues, on the other hand, can be prohibitive in some regions (Welke 2006).

The higher costs associated with woody biomass have made replacing cheap coal with wood challenging, as mentioned aboce.The properties of wood can be improved through the torrefecation of pellets to enable co-combustion with coal, but this is not yet cost competitive without external policy incentives (Wilén et al. 2014). For example, the paying capacity for torrefied pellets in Finland must exceed 35 €/MWH (i.e. equivalent to about 10.80 US$/GJ for an exchange rate of 1 US$=0.90 €) to be profitable.

Currently in Finland the delivered price of coal is only 20-25 €/MWH (i.e. 6.17-7.72 US$/GJ), including a CO_2 tax of 10 €/MWH (i.e. about 3 US$/GJ).

Replacing oil and gas are more promising from a market-driven perspective due to the much higher cost of these fuels compared with coal. Recent technological developments have enabled the production of drop-in diesel for vehicles and pyrolysis oil for replacement of heavy fuel oil. Although wood-based energy plants are roughly triple the price of gas or oil plants, lower fuel prices can compensate. As a result, 2 000-3 000 heat plants in Finland, Sweden and Denmark have started to use woody biomass to replace more expensive fuel oil.

2.2.4 Operational analysis

2.2.4.1 Current supply chain technology and system integration

Similar to other forest products supply chains, biomass flows from forest contractors to primary, secondary and tertiary production facilities, onward through channels of distributors and wholesalers before finally reaching the end-users (Figure 2.5). Levels of supply chain optimization and integration depend on the existing forest industry, the nature of regional forest ownership, drivers for biomass harvesting, and end-use goals. Supply chains evolving in different geographic regions are a product of regional conditions and have unique socioeconomic footprints.

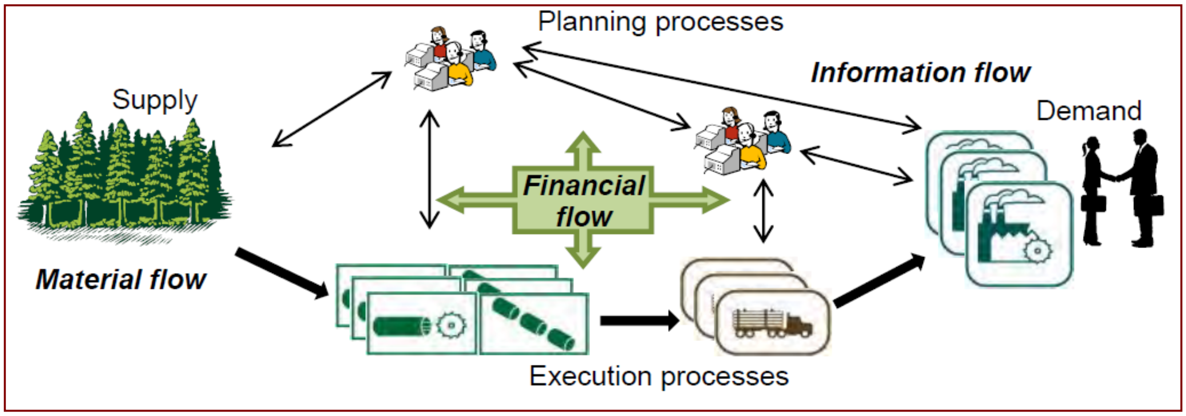


Figure 2.5. Forest product supply chain. Source: FORAC consortium.

Integration of biomass supply chains with existing forest management or use of cooperative structures in feedstock supply, management and long distant transport can achieve considerable cost savings and improve profitability across the supply chain. Increasing efficiencies in harvest and delivery can help biomass suppliers to manage risks; for example, in regions with high seasonal variation in biomass supply, using the same base machinery for harvesting different products from the forest can smooth demand peaks and ensure full operation of machinery year round. The most integrated and optimized biomass supply chains can be found in Nordic countries, especially Finland and Sweden.

2.2.4.2 Logistical analysis of current systems

Examples of highly efficient and competitive logistical systems

Nordic systems have the greatest efficiency for integrating roundwood with energy wood harvest. Single-grip harvesters pile residues onsite where they are seasoned for a few weeks in spring and summer to reduce moisture and allow needles to drop; they are then loaded onto a forwarder or farm tractor equipped with a grapple-loader and forest trailer and removed (Figure 2.6).

Figure 2.6. Integrated harvesting and transport of residual forest biomass and roundwood supply.

Although the above system is still the most commonly used for the harvest and removal of energy wood, harwarders (combined harvester-forwarder machines) have more recently been introduced for harvesting small trees for energy. Harwarders fell trees and cut them into ~ 6 m lengths for forwarding. The same machine also then forwards material to the landing, reducing the need for additional machinery. In small stands and over short forwarding distances, harwarders are emerging as a competitive alternative to manual felling or harvesters with modified grapples.

In Finland, stumps are sometimes also removed after final felling using excavators equipped with a lifting device (Laitila et al. 2008). Stumps are removed in one piece or are split into two or more pieces before being lifted. Splitting considerably diminishes the lifting force required, and a smaller area of the forest floor is disturbed and lifted with the coarse roots.

Chipping is the next step, which can take place in the woods, on the roadside, or at a terminal between the source and end use.The most efficient chipping is that which can be done at the terminal, because chips can be blown directly onto the ground so no trucks need to be present and waiting. If the terminal is near to the end-use facility there is also no need for trucks to transport, and chips can be fed directly into storage using front-end loaders (additional trucking is required if more than one end user is served by a terminal).

Integrating biomass harvesting with roundwood harvesting allows Nordic countries to use the same base machinery for both. This minimizes the capital costs tied up in harvesting machinery and smooths out the inefficiencies related to seasonal variations in biomass supply by keeping machinery running year round.

More efficient supply chains contribute to the economic competitiveness of forest bioenergy in Nordic countries. There are nearly 1 000 heating plants in Finland that use forest biomass and the majority of municipal centers have biomass heating plants. Nordic countries employ a number of other mechanisms to increase supply chain logistical efficiencies, including some of those described in the following section.

Opportunities to increase supply chain logistical efficiencies and reduce cost of delivered feedstock

Factors affecting the costs of biomass supply can be grouped into two main components: (1) the annual availability and quality of woody biomass around the planned bioenergy plant; and (2) costs to the user of feedstock associated with purchase, harvesting, processing, transportation, and storage.

More specifically, determining factors include: long distance transport to the plant; moisture content; stumpage; energy market fluctuations; labour and machine costs; and in Scandinavian countries also the location of the comminuting phase in the supply chain (Fagernäs et al. 2007).

As the use of woody biomass for industry and energy increases, the competitiveness of biomass becomes an important factor in reducing the availability of fuels. For example, the price of biomass decreases when demand for pulpwood is very low, and hence the energy industry can afford to purchase surplus wood for energy generation. In normal pulpwood demand situations, however, less wood is available for energy at a reasonable price.

Plant size is also an important factor. Larger plants tend to be more fuel-efficient but greater transport distances are needed to procure biomass, therefore operating costs increase. Additional fuel consumption also reduces lifecycle efficiency and emissions reductions for larger plants. From an economic point of view, optimal stands for biomass harvesting should have a high density of harvestable biomass, forwarding distances of less than 500 m and long transport distance requirements of less than 500 km.

The following are some specific ways in which operational efficiency can be increased:

1) <u>Better integrating woody biomass harvesting with existing forestry operations.</u>

2) <u>Increasing the productivity of machinery.</u>

3) <u>Improving moisture content management throughout the supply chain.</u> The procurement of forest biomass for energy production can be uneconomical due to high moisture content and low calorific value. Promoting systems with natural drying can help to reduce moisture in harvested biomass. Using the latest technology such as scales built onto load cells that allow the constant weighing of piles provides much more detailed sampling and allows for better moisture management (Erber et al. 2012).

4) <u>Improving biomass quality throughout the supply chain.</u> High quality of fuel wood depends also on ensuring proper heating value, particle size and amount of impurities. Ensuring a high quality fuel supply also requires relevant know-how on quality demands from customers and state-of-the-art technology to ensure reliable, on-time wood fuel deliveries (Röser 2012). Higher fuel qualities are also required when feedstock is used for value-added products such as pyrolysis oil and biodiesel (Huttunen 2011).

5) Responding to market demands. Liquid fuels like pyrolysis oil and biodiesel are more competitive than solid biomass, and producers will need to adapt to providing the most cost-competitive and in-demand products if market-driven mobilization is to be a success.

6) Producing higher-density intermediate products such as pellets and bio-oils. This opens up more distant markets to producing regions by decreasing relative transportation costs.

7) Smoothing out seasonal variations. Optimizing harvesting methods, storage points and storing time across the supply chain will increase competitiveness and flexibility. This can be done by: a) increasing storage capacity to be used in periods of low demand; b) finding alternative uses of storing production capacity during periods of low demand; and c) utilizing equipment from other operations during periods of high demand.

8) Improving conversion efficiencies. Uptake of CHP facilities in place of heat or power-only facilities will drastically improve process efficiency and reduce the amount of biomass required, thereby reducing costs. Emerging technologies should improve biomass conversion in existing modern applications.

9) Choosing optimal plant size and location. Proximity to biomass resources increases the economic competitiveness of a plant. Larger plants are more fuel efficient but require more biomass which must be sourced from further afield, increasing procurement costs (Jack 2009).

10) Improving operational quality to gain a positive reputation, increase competitiveness and reduce risks. This is most easily achieved where a skilled workforce, high levels of knowledge (e.g., knowledge of customer demands), trust among actors and state of the art technology are employed throughout the supply chain (Röser 2012). The most cost-competitive companies are those that can guarantee reliable, high quality deliveries for moderate prices in the medium and long term (Ikonen et al. 2013).

2.2.4.3 Feedstock availability at operational and whole supply chain scales

Operational availability is dependent on how physically and economically accessible biomass is in terms of recovery and transportation to bioenergy facilities. In some regions with plentiful biomass, operational availability can pose a challenge, especially where much of the fiber is inaccessible or the recovery rate too low to be economically viable.

The availability of woody biomass for bioenergy is regionally specific and highly influenced by a number of complex biophysical and socioeconomic factors that range from local, to regional, to global spheres. See Table 2.3 for a description of some of the various social, economic and biophysical factors that can impact biomass availability at operational scales. As residue harvest becomes more commonplace, optimization of logistics systems should lead to a more consistent and reliable supply to some degree, though political and economic incentives (e.g., the provision of subsidies or GHG credits for producers) may also be needed to increase operational availability and reduce risk and uncertainty.

Table 2.3. Political, social, and economic factors affecting operational availability. (Adapted from eXtension 2015).

Social and economic factors	
Energy prices	
Delivered costs of feedstock and energy products	Forest production technologies, transportation costs and energy conversion efficiencies will determine costs. Costs can be reduced through research and development and supply chain optimization.
Competing uses	Forest products markets will determine how much biomass is made available for energy applications. Pulpwood, timber and ecological services are all competing uses that can reduce biomass supply for energy applications (see also B.3).
Policy frameworks	The supply of forest biomass is affected by policies pertaining to forest management and utilization, energy, climate change, land use and environmental protection. Incentive programs for forest owners, bioenergy producers and consumers will also affect biomass supply.
Biomass market development	Landowners and forest managers will only make biomass available for energy if sufficient markets exist to sell into.
Social acceptance	The public must feel confident that biomass harvesting operations will provide local benefits (e.g., rural employment, investment in local economies) and that feedstock harvesting and energy production is safe and environmentally sustainable, among other factors.
Biophysical factors	
Physical conditions of site (e.g., terrain, forest density, site accessibility to machinery)	Residue availability can vary greatly from site to site depending on site conditions such as forest density, terrain, climate and weather, distance from end-user, etc. These can all affect physical accessibility and procurement and transportation costs.
Sustainability considerations	The production of forest biomass and bioenergy can have both positive and negative environmental implications. Forest thinning and biomass removal can improve stand health and these operations may increase biomass availability. Greenhouse gas reductions targets may also encourage use. Conversely, concerns over long-term soil fertility, biodiversity and watershed management necessitate careful planning and may limit forest biomass supply.

2.2.5 Sustainability and governance

2.2.5.1 Environmental sustainability

The increasing contribution of forest biomass to the global energy supply, especially in large-scale conversion facilities, is generating concerns about environmental sustainability. These concerns include maintenance of ecosystem services such as soil productivity, water quality, biodiversity, and carbon (C) balance/climate change mitigation potential of forest bioenergy.

Emerging bioenergy markets typically first take advantage of secondary residue streams of various wood processing industries and tertiary end-of-life residues. The use of these secondary wood resources is not likely to compromise environmental sustainability of forests. When these residues in any region become scarce or fully utilized, primary residues such as branches, tops, and whole trees become increasingly targeted as feedstock sources. Forest biomass procurement in the boreal and temperate biomes should therefore not be analyzed as a stand-alone activity, but rather an intensification of land use and of forest management, in which tree parts and trees are harvested in addition to harvest for conventional wood products.

Thus, principles of protection and sustainability should remain the same whether forests are managed for conventional wood products only or also for biomass for energy. Some modifications may be needed to properly identify and find mitigation strategies for sensitive conditions where evidence suggests that the incremental removal of biomass or other forms of intensive management may not be sustainable. Silvicultural practices such as fertilization, competition control, and soil preparation are options to manage the microenvironment and tree growing conditions and to prevent or mitigate negative impacts. Forest biomass procurement practices should therefore be seen as an integral part of silviculture. Moreover, landscape management regulations should be enforced to ensure that sufficient biodiversity-important features such as dead wood, aging stands, corridors, etc. are preserved. Special attention should then be directed to trees and stands that, without a bioenergy market, would have been left uncut. Greater emphasis should also be placed on linking practices to functional values of interest within ecosystems.

One important driver for introducing bioenergy is the assumption that its use can help mitigate C emissions and stabilize atmospheric C concentration levels. However, the “carbon neutrality” assumption of bioenergy has been widely criticized (Johnson 2009, Searchinger et al. 2009). Two main points of critique include: (1) that combustion of biomass will emit its C content to the atmosphere immediately, whereas if left in the forest it would decompose, its C content partly accumulating in the soil and partly released to the atmosphere over time, and (2) the energy output per unit of C emitted is lower for biomass than for fossil alternatives. This creates a *“payback time”*, which describes the time lag between the point of biomass harvest (and thus conversion and C release) and the point in time when the same (absolute) or a reference (relative) forest and energy system reach the same C concentration levels. This time difference has caused debate as to whether bioenergy is able to help achieve near-term GHG reduction targets (Cowie et al. 2013).

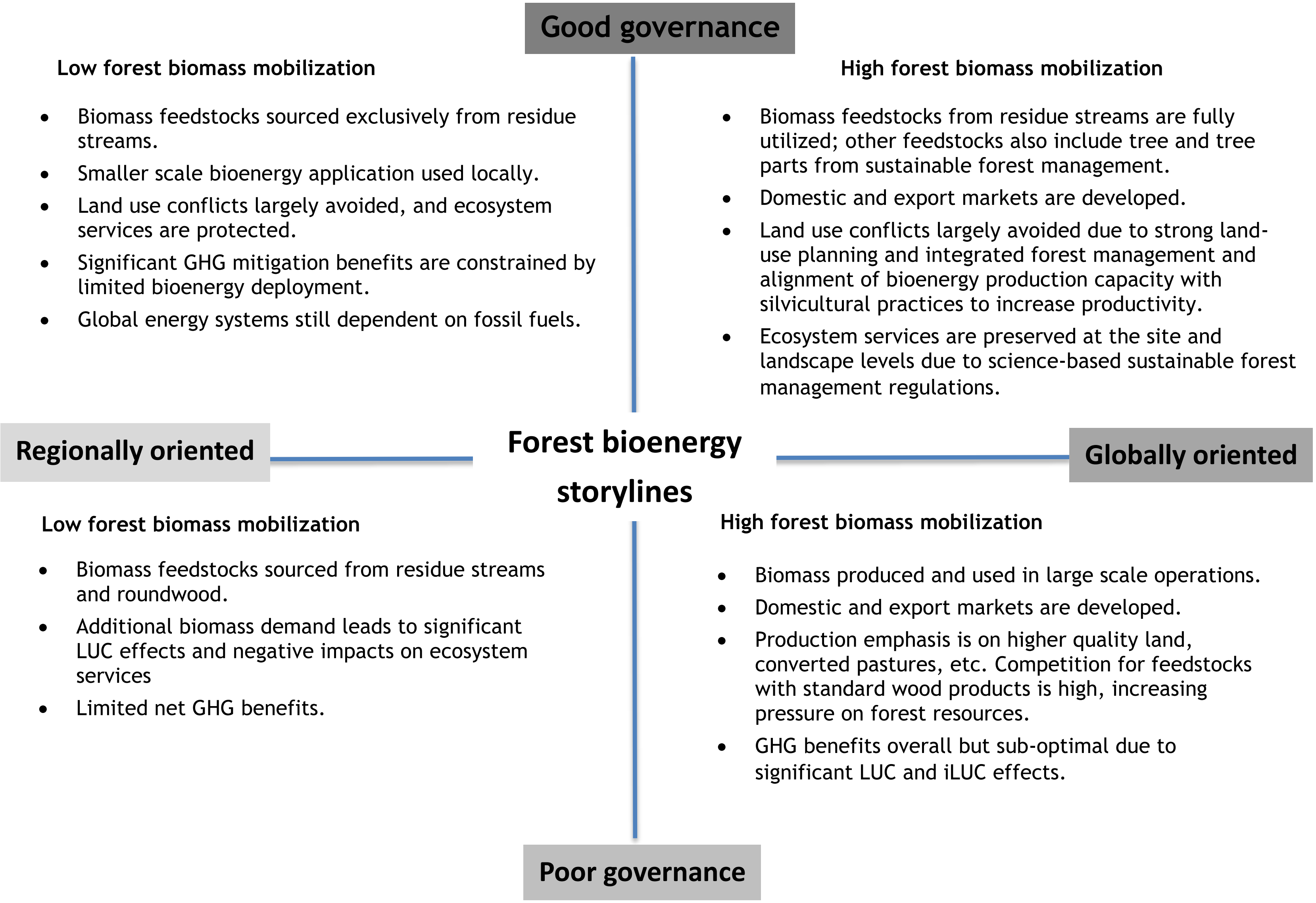
The payback time is assumed to be particularly long for coarse woody biomass like stumps and stemwood from long-rotation forestry since they decompose more slowly than tree tops and branches, if left in the forest (Repo et al. 2012). It has therefore been argued that stemwood should not be used as a source for bioenergy (Agostini et al. 2013). Although the analyses are right, there are reasons to question this conclusion. Mitigating global warming is a long-term rather than a short-term objective. Therefore, short-term increases in GHG emissions as a result of using biomass from long-rotation forestry as an energy source will eventually turn into long-term GHG reductions as compared to fossil alternatives (Dehue 2013). Transitioning to an energy system devoid of fossil fuels and based on renewable sources might require some short-term increases in emissions, as long as they are part of a larger transition plan, which should include preparing the forestry sector for a future situation where it is expected to provide biomaterials and bioenergy.

2.2.5.2 Governance

Chum et al. (2011) developed four different storylines for biomass deployment on a global scale by 2050. Adapting these storylines to the specific context of forest biomass gives scenarios distributed according to two dimensions, governance and level of globalisation. Figure 2.7 suggests that high biomass deployment levels can be reached in several different ways, but that good governance mechanisms that cover all aspects of sustainability, (i.e. environmental, social and economic) such as science-based improvements of practices including increasing the awareness of the forestry sector for a future situation where it is expected to provide both conventional forest products, biomaterials and bioenergy, is needed to ensure mobilization of sustainable forest biomass supply chains. This also suggests that high levels of sustainable mobilization would require high levels of globalization of supply chains, for example through more technology and knowledge transfer across regions, bioenergy late-comers could leap-frog towards state-of-the art technology and practices developed in countries with a longer history of bioenergy deployment, and also globally harmonized sustainability requirements and certification systems (Chum et al. 2011).Trans-boundary forms of governance such as the EU Renewable Energy Directive have been gaining acknowledgement as important drivers of change (Andonova and Mitchell 2010), and have been shown to be important predecessors for other like-minded initiatives elsewhere in the world (Afionis and Stringer 2012). However, In 2014, the European Commission announced that it will not pursue binding sustainability criteria to regulate the production of woody biomass for energy purposes before 2020 (EC 2014). Across North-West (NW) Europe, large power and heat production utilities (including Electrabel/GdF Suez, Dong, Nuon, RWE/Essent/npower, Vattenfall, E.ON) aiming at importing wood pellets from overseas initially formed the International Wood Pellet Buyers Initiative (IWPB) which has recently been institutionalized as the Sustainable Biomass Partnership (SBP). The SBP sets forth minimum quality and sustainability requirements for wood pellets (Ryckmans 2013), which are reflected in the voluntary schemes used by several large utilities, including Electrabel in Belgium (Laborelec scheme), or Essent/RWE/npower in the Netherlands (Green Gold Label).

Despite these initiatives, in internationally-oriented EU markets, a national adoption of the sustainability criteria laid out in the Renewable Energy Directive (RED), or similar criteria, is likely and in case of the UK, the largest single market for traded wood pellets, already proposed. As of 2015, the UK will restrict forest material to assortments that achieve at minimum 60% GHG emission savings against the EU fossil electricity average and require proof of sustainable forest management (SFM). Eligible SFM schemes for the UK market include the Forest Stewardship Council (FSC) and schemes endorsed by the PEFC, such as the Sustainable Forestry Initiative (SFI). In the Netherlands, the energy industry and non-governmental organization (NGOs) have discussed the Energy Accord since the beginning of 2014 and achieved principal agreement on the sustainability criteria for solid biomass. While specific criteria have been laid out, key questions that remain are how compliance will be tested and monitored, e.g. which existing SFM certification system will be approved as proof of meeting (which part of) the criteria. In the Flemish part of Belgium, a proposal is being prepared to bring the sustainability requirements for woody biomass to the level of bioliquids. In the Walloon region in Belgium, since 2006, value chain GHG reduction compared to fossil is decisive for the amount of green certificates received. In Denmark, a voluntary industry agreement is set to ensure 40% and 100%

sustainable biomass use for bioenergy in 2016 and 2019, respectively. On the supply side, although only a small share of global forest areas relative to the total global forest land mass is governed by any sustainable forest management system (Rekacewicz et al. 2009), the highest certification volumes are in boreal and temperate forests in Northern Europe, Canada, and the US. By 2012, 151 million ha of forest were certified by the Forest Stewardship Council (FSC), 88% of which were in the temperate and boreal forest biomes of North America, Europe, and Russia (FSC 2012). FSC certification shares of total managed forest areas are 6% for the US, 18% for Canada, 5% for Russia, and 32% in the EU-28. Apart from Russia, these shares fall behind those of certification under the Program for the Endorsement of Forest Certification (PEFC) umbrella scheme, which approved several national certification schemes, including Sustainable Forest Initiative in the USA and Canadian Standards Association in Canada. PEFC-certified, managed forests cover 15% in the US, 39% in Canada, and 69% in EU-28 of all managed forest area.



Good governance

Low forest biomass mobilization

- Biomass feedstocks sourced exclusively from residue streams.
- Smaller scale bioenergy application used locally.
- Land use conflicts largely avoided, and ecosystem services are protected.
- Significant GHG mitigation benefits are constrained by limited bioenergy deployment.
- Global energy systems still dependent on fossil fuels.

High forest biomass mobilization

- Biomass feedstocks from residue streams are fully utilized; other feedstocks also include tree and tree parts from sustainable forest management.
- Domestic and export markets are developed.
- Land use conflicts largely avoided due to strong land-use planning and integrated forest management and alignment of bioenergy production capacity with silvicultural practices to increase productivity.
- Ecosystem services are preserved at the site and landscape levels due to science-based sustainable forest management regulations.

Regionally oriented

Forest bioenergy storylines

Globally oriented

Low forest biomass mobilization

- Biomass feedstocks sourced from residue streams and roundwood.
- Additional biomass demand leads to significant LUC effects and negative impacts on ecosystem services
- Limited net GHG benefits.

High forest biomass mobilization

- Biomass produced and used in large scale operations.
- Domestic and export markets are developed.
- Production emphasis is on higher quality land, converted pastures, etc. Competition for feedstocks with standard wood products is high, increasing pressure on forest resources.
- GHG benefits overall but sub-optimal due to significant LUC and iLUC effects.

Poor governance

Figure 2.7. Forest bioenergy storylines. Adapted from Chum et al. (2011).

2.3 SYNTHESIS OF SOLUTIONS FOR MOBILIZATION

Although a first obvious driver to increased use of forest biomass for bioenergy is policy-supported price, solutions and opportunities for increased mobilization can still be found in all aspects of the supply chain.

2.3.1 Technological and institutional learning

The variability of forest biomass supply chains between countries can be seen as a challenge, but it also offers opportunities for further mobilization by multiplying the occasions of technological and institutional learning, i.e. :

- learning-by-searching;
- learning-by-doing;
- learning-by-using;
- learning-by-interacting; and
- upsizing (or downsizing) a technology.

A (yet theoretical) example of the role of learning, and particularly upsizing, is that of the deployment of the cellulosic biofuel industry in the US. The current pilot and demonstration plants rely on a conventional supply chain where corn stover is baled, stored at fieldside, and delivered in low-density format to the biorefinery. To achieve cost-competitive production and conversion levels, however, larger facilities are required that enable economies of scale. Such facilities also require a scale-up and transition of the logistics supply system with a steady supply of quality feedstock. This will require a more advanced feedstock supply system that includes pre-processing. Conversely, the ramping up of internal bioenergy demand in Canada could contribute to diversify forest biomass end-use markets and reduce business and investment risk, which would strenghten, stabilize or even expand Canada’s biomass international trade of wood pellets by making supply chains more efficient and cost-competitive.

Simple technology transfers from one supply chain to the other is not enough to create successful business cases. Technology and know-how need to be combined with existing expertise. An example of this would be economically successful business models that combine calculations of economically and technologically available resources made by experts, local knowledge of practitioners (e.g. effective work methods) and social innovations made by local entrepreneurs (e.g. forest bioenergy cooperatives).

2.3.2 Trade

Trade offers opportunities/incentives for biomass mobilization. So far, cross-border and regional trade dominate the bioenergy sector with respect to forest biomass. Fuel wood, charcoal, wood chip, and wood waste trade volumes are almost exclusively regional or cross-border, due to limited homogeneity and bulk density (e.g., fuel wood), high moisture content (e.g., wood chips) as well as a lack of handling equipment (e.g., in transloading stations). A wider and growing international trade of forest bioenergy feedstocks has so far only been observed for wood pellets. Trade can enable the creation or re-establishment of logistic systems, required for a national mobilization of biomass. The current expansion of the U.S. wood pellet production capacity, destined for export to the European Union, could provide a market and logistical "stepping-stone" to the transition of the U.S. feedstock supply system mentioned above (which is required for the scale-up of the U.S. biorefining industry).

2.3.3 Cooperative organization structures

One social innovation for increasing supply chain mobilization is the expansion of markets throughout cooperative organization structures, such as:

- Forest biomass supply cooperatives;
- Forest biomass energy firms; and
- Forest biomass trade centers.

The open exchange of information, best practices and market instruments like long-term contracts could be used to improve cooperation between forest owners, entrepreneurs, forest owner groupings and forest industry to secure supply and demand. Furthermore, support for cooperative organization structures (including items such as the development of professional corps, associations, and formal educational programs) can also be a way to increase the professionalisation of the workforce in forest biomass supply chains, which has been identified as one important driver for increased biomass mobilization.

2.3.4 Integration of energy and forest systems

2.3.4.1 Management of biomass quality

One important step in forest biomass mobilization is collaboration among the stakeholders along the supply chain. This includes client interaction to get a better understanding of their needs in terms of end-product characteristics. Also, developers of technologies that utilize woody biomass should ensure that the technologies developed are robust enough to use the variety of available forest biomass resources. On the other hand, biomass suppliers need to ensure strict quality management. Biomass quality is very important to ensure conversion process efficiency and thus the profitability of the whole forest biomass-to-energy chain. Limited or low quality forest fuel causes risks to the downstream processes, and unscheduled stoppages lower the profitability of cost-sensitive processes, such as heat production.

2.3.4.2 Integrated planning of bioenergy and conventional wood products

Adequate characterization and sorting of wood fiber as early as possible in the supply chain, even directly in forest stands, if possible, can provide strategic information that can help to make economic and environmental management decisions on treatments for individual trees and forest stands, improve thinning and harvesting operations, and efficiently allocate fiber resources for optimal utilization. This should increase the profitability of the entire forest product value chain (including both conventional products (e.g. sawnwood, pulp and paper and bioenergy) as a result of two processes: first, proper identification, inventory and management of biomass for bioenergy (i.e. unutilized fiber by conventional wood product industries) should increase the total volume of wood harvested per unit area of land, and thus decrease overall harvesting costs per cubic meter. Secondly, the addition of various bioenergy pathways in the forest product value chain should improve the sorting capacity of fiber throughout the chain, thus ensuring that only feedstock of suitable quality is processed into each forest product.

Fiber terminals, where fiber can be sorted and preprocessed, can play a key role in the provision of such flexibility, and links back to the above-mentioned cooperative organization structures. For biomass producers, fiber terminals could also ensure that forest machinery can be utilized effectively year-round. Since raw forest biomass cannot be transported long distances due to its relatively low value, robust value-upgrading at terminals close to the feedstock sources before long-distance transportation could be considered.

Related to integrated planning, there are many different silvicultural practices that could be modified/enhanced in such a way as to incorporate the future forest biomass market considerations at earlier planning stages so that the combined productivity of conventional wood product markets and forest bioenergy markets may be fully developed and achieved. Forest industry and energy producers should work jointly on the interoperability of specifications and measures (volumetric and energetic) as well as common terminology and conversion factors related to wood for energy.

2.3.4.3 Conversion efficiency and cascading use

Also relevant to integration of forests and energy systems is the efficient use of biomass resources. One of the indicators for improved use of biomass for energy is improving conversion efficiency. Also, limited forest biomass resources can be used more efficiently through cascading systems. Cascading means that the forest product value chain is optimized both in added value and in GHG reduction. Reporting, monitoring and research on conversion efficiency and cascading use, and policy measures that encourage them, could therefore be an important step towards increased and improved use of sustainable biomass resources.

2.3.4.4 Integrated forest land planning for energy, conventional wood products and ecosystem services

Forest management approaches aimed at the production of forest bioenergy (along with conventional forest products) should focus on strengthening existing environmental synergies between this production and the other forest functions. These synergies include, for example, forest fire protection, conservation balanced soil nutrients, and in some instances support of biodiversity and water quality.

2.3.5 Development of a shared vision

2.3.5.1 Recognition of different views and understandings

Constraints related to social acceptance (e.g. evidence of activities becoming ‘trusted’ or ‘taken for granted’ by stakeholders in the general public and in markets) can influence their deployment in a relatively short timeframe. Such issues need to be recognised and must then be factored into longer term plans for the development of the sector. The simple detection and formal recognition of different scientific understandings or different views of environmental history can contribute to produce new knowledge, shed new light on the environmental consequences of bioenergy policy and possibly bring stakeholders closer to a shared vision.

2.3.5.2 Development of common sustainability criteria

Whether bioenergy development will be beneficial or detrimental for forests and to those people who depend on forests for their survival depends on the rules, standards and incentives for biomass production. Development of sustainability criteria for bioenergy is part of the shared vision described above. Stakeholders along forest biomass supply chains clearly recognize that there is a need to substantiate the sustainable production of biomass. A dialog driving policy makers to come to internationally accepted sustainability requirements for bioenergy commodities could create new opportunities for sustainable mobilization and bioenergy trade.

2.3.5.3 Development of technical standards

The same could be said about the need for technical standardization of bioenergy products. The development of standards, such as the mandates given by the European Commission to the Europan Committee for Standardization (CEN), can help remove trade barriers, increase market transparency and increase public acceptance. The fact that the major producing regions have already started to compare and align their technical standards is a sign that international policy cooperation may lead to new opportunities for international bioenergy trade.

2.4 ESTIMATES OF POTENTIAL FOR FOREST BIOMASS MOBILIZATION

Simple estimates of potentials of forest biomass feedstocks that could be mobilized for bioenergy production can be derived from the size of the forestry and bioenergy sectors relative to the theoretical capacity of forest ecosystems in a given country. For this purpose, two indicators of forest biomass feedstock potential were calculated using data from international agencies :

- the ratio of domestic roundwood production to forest ecosystem net primary production (NPP), and
- the ratio of forest bioenergy production to domestic roundwood production.

All input data were converted to units of carbon per year so that they could be used to estimate ratios. The ratio of Roundwood production-to-NPP gives an indication of forest management intensity within a given country. The ratio of Bioenergy-to-Roundwood production gives an indication the quantity of bioenergy feedstock resources that is mobilized relative to the quantity of roundwood produced for each country.

Caculations of these indicators for a suite of countries from the boreal and temperated biomes (Table 2.4) using average data for the period 2002-2013 are shown in Table 2.4. Ratios vary widely among countries, demonstrating that mobilization of forest bioenergy is relatively high in some countries (e.g., Germany), while significant gains could be achieved in others (e.g., Canada).

For countries that import large quantities of roundwood relative to domestic production, such as Denmark and Belgium, the value for Bioenergy-to-Roundwood production is likely biased by the amount of secondary residues produced during the processing of imported roundwood and used for bioenergy. Conversely, countries that export large quantities of roundwood exhibit low ratios of bioenergy-to-roundwood production (e.g., New Zealand). Given the substantial flow of wood imports and exports among countries, the values reported here must therefore be interpreted with caution.

Table 2.4. Roundwood-to-NPP and Bioenergy-to-Roundwood ratios

	Roundwood-to-NPP %	Bioenergy-to-Roundwood %
Australia	0.3	74
Belgium	22.3	81
Canada	2.5	36
Croatia	9.5	43
Denmark	14.9	231
Finland	12.4	72
Germany	16.7	83
Ireland	9.5	33
New Zealand	4.2	26
Norway	4.7	57
Russia	1.2	9
Sweden	11.2	59
United States	5.5	64

Despite caveats, these indicators reflect how mobilization of forest biomass can be investigated at two levels:

- the intensification of forest management activities, in which forestry would appropriate a larger share of forest ecosystem net primary productivity, and
- the intensification of biomass recovery from silvicultural, harvesting and wood processing operations, in which bioenergy would appropriate a larger share of forestry by-products/residues.

Table 2.5 summarizes projections of solid biofuel production according to various scenarios of increasing mobilization, namely :

- Scenario 1 : an increase of the Bioenergy-to-Roundwood ratio to a minimum of 50% for all studied countries, a ratio that is surpassed by most European countries but well above the ratio observed in important forest countries such as Canada and Russia;
- Scenario 2 : an increase of the Bioenergy-to-Roundwood ratio to 83% for all studied countries, the highest ratio observed among the studied countries;
- Scenario 3 : an increase of the Roundwood-to-NPP ratio to a minimum of 10%, equivalent to the current average ratio among the studied countries;
- Scenario 4: an increase of the Roundwood-to-NPP ratio to a minimum of 10% and the Bioenergy-to-Roundwood ratio to a minimum of 50%; and
- Scenario 5: an increase of the Roundwood-to-NPP ratio to a minimum of 10% and the Bioenergy-to-Roundwood ratio to 83%.

The Renewable Energy Roadmap (Remap) 2030 of IRENA is based on projections from Smeets et al. (2007) for biomass from forestry, for various biomass categories and world regions (Table 2.6). Projected values for IRENA's Low scenario, in which forest harvesting operations are limited to forest areas already under management, are close to our Scenarios 2 and 3 (Table 2.5), which either involve a larger appropriation of forestry by-products/residues for bioenergy production, or a larger appropriation of forest ecosystem productivity by the forest sector (both for conventional and bioenergy products). On the other hand, our projections for Scenario 4 and 5 mobilize 19 and 28 EJ year^{-1}, respectively, which is fairly close to to the level of IRENA's High scenario (Table 2.6); this suggests that achieving such a level of moblisation would require a strong mix of both intensification of biomass biomass recovery from silvicultural, harvesting and wood processing operations, and of forest management activities.

This analysis reveals the crucial role played by Russia in global mobilization of forest bioenergy: to fulfill the country's expected contribution to global targets (i.e. up to 10.48 EJ year^{-1} in our scenario 5, up from an average of 0.14 EJ^{-1} in the 2002-2013 decade), considerable efforts will be required in institutional learning and capacity-building over a relatively short time-frame. On the other hand, our projections seem to grossly estimate the level of forest biomass mobilization that can occur in countries from Oceania, as comparison with IRENA's estimates shows differences of orders of magnitude. Our approach likely fails to properly capture the correct NPP of those countries, which show contrasting vegetation relative to other countries from the boreal and temperate biomes.

Some of the solutions for mobilization highlighted in this chapter address the first of the two processes for increasing mobilization, i.e. intensification biomass recovery from forestry activities: improving logistics and conversion technologies, increasing quality management of biomass, developing cooperative organization structures that would support stakeholders along the supply chain, will make it possible to increase efficiency of practices and extract more energy (and value) from harvested wood within similar but modernized infrastructures and frameworks of forestry sectors as they currently exist. Technological learning would play an important role in this modernization. Such improvements over the next decades would likely allow to reach projections similar to those of Scenario 1 (medium modernization), or Scenario 2 (important modernization), with mobilization of forest biomass from boreal and temperate biomes providing 5 to 7 EJ year^{-1} (Table 2.5).

This is, however, still a far cry from targets set by agencies. According to our calculations, more substantial gains in mobilization can only be achieved with an increase in forest management intensity causing an increase in the appropriation of forest NPP, such as projected in Scenarios 3 to 5 (14 to 28 EJ year^{-1}) (Table 2.5). Since sustainability issues are more likely to arise with intensification of forest management, strong governance schemes and globally accepted sustainability criteria would be all the more necessary. Moreover, such an increase would likely require a fundamental shift in the forest and energy systems of many countries. For example, for Canada, reaching a Roundwood-to-NPP ratio of 10% would entail a tripling of current annual allowable cut (AAC); this would require a quite drastic increase in silviculture practices, which are currently largely based on extensive forestry, and an opening of yet untouched forest areas (currently mapped as non-commercial, both due to ecological reasons and economic reasons e.g. road access). The first step in such a momentous shift towards more intensive forestry would indeniably be the development of a shared vision, in which social actors would agree on a collective vision of the future national and global forestry and energy systems in which bioenergy would occupy a significant place, a considerable societal change for Canada.

Table 2.5. Projections of forest biomass production for selected countries. Data are in EJ year^{-1}.

		Projected production with a minimum of…				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Country	Production of solid biofuels (average 2002-2013)	bioenergy: roundwood=50%	bioenergy: roundwood=83%	roundwood:NPP = 10%	roundwood:NPP= 10% and bioenergy: roundwood=50%	roundwood:NPP= 10% and bioenergy: roundwood=83%
Australia	0.19	0.19	0.21	5.63	5.63	6.37
Belgium	0.03	0.03	0.03	0.03	0.03	0.03
Canada	0.48	0.68	1.12	1.91	2.66	4.43
Croatia	0.02	0.02	0.03	0.02	0.02	0.03
Denmark	0.04	0.04	0.04	0.04	0.04	0.04
Finland	0.31	0.31	0.35	0.31	0.31	0.35
Germany	0.38	0.38	0.38	0.38	0.38	0.38
Ireland	0.01	0.01	0.02	0.01	0.01	0.02
New Zealand	0.05	0.09	0.15	0.11	0.22	0.36
Norway	0.05	0.05	0.07	0.10	0.10	0.14
Sweden	0.35	0.35	0.49	0.35	0.35	0.49
US	2.06	2.06	2.69	3.74	3.74	4.88
Russia	0.14	0.74	1.23	1.19	6.31	10.48
Total all countries	**4.09**	**4.94**	**6.82**	**13.80**	**19.79**	**28.01**
North American countries	**2.54**	**2.74**	**3.81**	**5.64**	**6.40**	**9.31**
European countries	**1.31**	**1.92**	**2.64**	**2.41**	**7.54**	**11.97**
Oceanian countries	**0.23**	**0.28**	**0.36**	**5.75**	**5.85**	**6.74**

Note: North American countries: Canada and the US. European countries: Belgium, Croatia, Denmark, Finland, Germany, Ireland, Norway, Sweden and Russia. Oceanian countries: Australia and New Zealand.

Table 2.6. Projections from Smeets et al. (2007) used as basis for IRENA Remap. Data are in EJ year^{-1}.

	Surplus forest growth	Logging and processing residues	Total
Low scenario			
Europe	0	3.60	3.60
North America	0	6.20	6.20
Ocenia	0	0.60	0.60
Global	0	14.5	14.50
High scenario			
Europe	14.00	4.70	18.70
North America	0.20	6.20	6.40
Ocenia	0	0.60	0.60
Global	14.60	17.10	31.70

Note: Europe includes East and West Europe, the Baltic States and the Commonwealth of Independent States (including Russia). The High scenario corresponds to the economic potential, i.e. the total potential that can be produced at economically profitable levels in the areas of available supply. The Low scenario corresponds to the ecological-economic potential, i.e. the total biomass based on wood production and utilization that are limited to forests currently under commercial operation.

2.5 CONCLUSION

Forest biomass supply chains are not a single entity. Several supply chains have proven economically viable and sustainable; others not. Objectives and policies for bioenergy (and more largely also for renewable energy), which are typically agreed upon at higher decision making levels, should rather be defined and implemented at lower decision making levels to effectively integrate renewable energy into the existing energy systems. Local strategies can assist in translating national plans to local level action while allowing for local level prioritisation and ownership. In addition, while local planning could facilitate the identification of the most favourable sites and technologies, it may also improve the understanding of the local environment and its actors, and facilitate the integration of policies throughout various sectors to cater for regional complexity.

Finally, national governments around the world have different reasons as well as different available resources for increasing the production and use of forest biomass. Thus an essential first step in designing appropriate bioenergy policies is to distinguish between the needs and resources of individual countries. Ultimately, policies should be technology- and feedstock-neutral and enable an organic industry transition, from currently predominantly bioenergy focused supply chains to supply chains that deliver feedstock to a range of conversion and utilization routes in the future bio-based economy.

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3
AGRICULTURAL CROP RESIDUES

3.1 INTRODUCTION

With concerns over food security and land use change from first generation biofuels (e.g., bioethanol from grain and sugar, and biodiesel from oilseeds) and the development of new technologies to turn waste products and non-food components of agricultural crops into advanced biofuels and other valuable bioproducts, agricultural residues are of increasing interest as a source of biomass for bioenergy and biorefining applications.

Agricultural residues are classed as primary residues originating directly from the fields (e.g., straw, leaves, stover, stalks, husks, cobs) or secondary residues originating from industrial processing (e.g., pits, shells, peels, husks) (Torén et al. 2011). Animal livestock wastes are also considered to be agricultural residues, but these are addressed in the biogas section of this report.

Agricultural residues provide a potentially attractive source of biomass in that they do not directly require additional land to produce and can be harvested alongside more high-value agricultural products (e.g. food and fodder grains). Harvesting residues for bioenergy applications can provide additional income to agricultural operations, by giving these residues financial value. Partial residue removal in high yielding fields can also benefit agricultural productivity by speeding up soil warming and allowing for earlier seeding in cooler climates.

However, diverting residues to bioenergy and biorefining applications may face competition from other uses of residues, e.g. animal feed or bedding. Plus a certain amount of residue needs to be retained for environmental sustainability. As residue harvest removes carbon, nitrogen and other nutrients from the site and reduces snow capture, maintaining a minimum amount of residues on fields is essential for long-term soil fertility and protection against erosion. As such, residue retention levels depend on soil type, rainfall, slope and crop rotation among other factors.

Various bioenergy targets have been set to meet different goals for energy security and climate change mitigation. The International Renewable Energy Agency (IRENA) estimates that 13-30 EJ per year of agricultural residues must be used by 2030 to meet the Sustainable Energy for all (SE4All) target of doubling the share of renewable energy in the global energy mix before 2030 (Nakada et al. 2014). Meeting the targets set by the Global Energy Assessment (GEA 2012) requires extensive use of agricultural residues resources, with an estimated technical potential of 49 EJ per year. The demand for crop residues is not specified in the published IPCC projections (Bruckner et al. 2014).

Bentsen et al. (2014) estimates that the current global theoretical potential of primary agricultural residues from cereals and sugar cane is approximately 3.7 x 10^9 metric tonnes of dry matter annually, corresponding to ~65 EJ per year. Earlier studies find the theoretical potential of cereals and sugar cane to 2.7 – 3.5 x 10^9 metric tonnes per year (Smil 1999, Lal 2005, Krausmann et al. 2008, Hakala et al. 2009), corresponding to 47-61 EJ per year. Cereals and sugar cane may account for 80% of the total residue production (Lal 2005) and constitute the most harvestable part.

The technical potential of agricultural residues (logically) is significantly smaller. First, a certain amount of residues must be left on site to protect soil productivity. Scarlat et al. (2010) summarize research on sustainable removal rates for a number of crops, and report rates between 15 and 60% for most crops. Secondly, the current use of crop resides is poorly known (Bentsen et al. 2014). Very few countries collect data on agricultural residue production and use as part of their surveys or census work, but a number of modelling studies find that the current level of utilization on a global level (including for energy) is 2.9 x 10^9 tonnes per year (66% of total production) (Krausmann et al. 2008, Rogner et al. 2012). Wirsenius (2003) finds a somewhat contradictory result, estimating the fraction of agricultural residues utilized by humans to be 41%. The IPCC special report on renewable energy (Chum et al. 2011) reviewed the vast body of literature on bioenergy resources and reports a technical potential of agricultural residues by 2050 of 15-70 EJ per year, i.e. enough to meet the SE4All target, but not necessarily enough to meet the GEA target.

This multi-country case study assesses the potential opportunities and barriers to the mobilization of agricultural residues for bioenergy and biorefining in Denmark, the USA and Canada. Collectively, these case studies show that there is a real potential for further development of viable bioenergy and biorefining supply chains based on agricultural residues, if there is political support, best practices are followed for residue removal, and there is continued supply chain development and optimization.

3.2 BIOENERGY AND FEEDSTOCK PRODUCTION SYSTEM ANALYSIS

3.2.1 Factors affecting market demand

3.2.1.1 Economic and political drivers for energy and feedstock production

Denmark

In Denmark, the main rationale to initiate energy production from agricultural residues was energy security. Renewables, nuclear power and natural gas became priorities for the nation during the oil crisis in 1973-74, to increase national energy security (Nygård 2011). In the 1986 “Electricity Agreement” instalment of 80-100 MW, combined heat and power (CHP) production based on domestic fuels such as straw, natural gas, woodchips or biogas was stipulated. In 1993, the “Biomass Agreement” mandated the use of 1.2 million tonnes of straw and 0.2 million tonnes of wood chips by 2000, with revisions in 1997 and 2000 to increase flexibility and attainability. In the late 2000s, the focus shifted from energy security to creating a fossil free future (Nygård 2011), and feed-in tariffs for renewables increased.

The Danish National Renewable Energy Action Plan to meet the targets of the EU’s Renewable Energy Directive (RED) requires a slight increase in the use of straw (an additional 500 TJ (~350 metric tonnes) to be used for energy by 2015 and 1000 TJ (~700 metric tonnes) by 2020 compared to the 2005 use) (Klima og Energiministeriet 2010). Danish goals for the use of straw over the past 20 years have led to a well-developed supply chain supported by mandated use and/or financial incentives throughout.

USA

Security of energy supply and a diversification of transport fuel supplies are some of the drivers to promote the production of renewable transport fuels in the USA. A biofuel target was set via the Renewable Fuels Standard (RFS2), which required the annual use of 9 x 10^9 gallons (34 x 10^9 litres) of biofuels by 2008. This target is set to increase to 36 x 10^9 gallons (136 x 10^9 litres) by 2022, of which at least 16 x 10^9 gallons (61 x 10^9 litres) shall be of cellulosic origin, e.g., crop residues. Other than that, there is currently no federal policy promoting the specific use of agricultural residues for energy. Individual states have renewable portfolio standards in place that prescribe a minimum share of renewable energy (mostly power) generation, but agricultural residues are not used in large quantities to meet these targets (Hess et al. 2015).

Canada

In Canada, the drivers for the development of bioenergy and biorefining have changed over time. The forest products industry remains the major producer and user of bioenergy in Canada, generating 522 GJ heat and power in 2013 (Statistics Canada, 2015). It was the oil crisis in the 1970s and pollution concerns that led the forest products industry to install hogfuel and recovery boilers, and move to energy self-sufficiency. Public R&D investments supported the development of new conversion technologies, including gasification, pyrolysis and biochemical conversion of lignocellulose. In the 1990s, climate change mitigation became an important motivator for bioenergy and renewable energy R&D. One decade later, the first-generation biofuels industry emerged along with growth in solar and wind energy installations. Around this same time, the forest products industry initiated its transformation program to reinvent itself for the new century.

Canadian biofuel mandates of 5% renewables in the gasoline pool and 2% renewables content in the diesel pool are being met through domestic production of 1G biofuels and imports. While both agriculture and forest residues exist in substantial quantities and the pulp and paper industry is seeking to diversify its product mix, the poor economics of cellulosic ethanol present a significant disincentive for large-scale ethanol production based on residues.

Instead, agricultural crop residues are being studied as sustainable feedstocks for biorefinery applications that produce high value chemicals and bioenergy. The conversion of agricultural residues into higher-value bioproducts, such as cellulosic sugars for chemical production, makes a stronger business case.

3.2.1.2 Overview of existing and potential markets for crop residues

Denmark

The Danish market for primary crop residues is dominated by cereal (wheat, barley) straw. The annual production varies around 6 million metric tonnes with cereal straw accounting for 90% or more. Rape seed straw accounts for the remainder, except a marginal contribution of residues from pulses (0.1 – 0.3% of the annual crop residue production).

The use of residues in different markets varies from year to year. In the 2006 to 2014 period 50 – 60 % of the production has been used for energy, feed/fodder or bedding, with energy purposes appropriating a little less than 50 % of the harvested amount.

USA

Crop residues are desirable feedstocks for bioenergy applications due to their low cost, immediate availability, and relatively concentrated location in major grain growing regions (US DOE 2011). At this point, non-energy uses, including feed and fodder, animal bedding, mushroom cultivation, chicken hatcheries, etc., are the main application for agricultural residues in the USA. The production of cellulosic biofuel however is increasing. In 2014, three new biorefineries utilizing corn stover as their primary feedstock came online in Kansas (Abengoa) and Iowa (POET/DSM and DuPont).

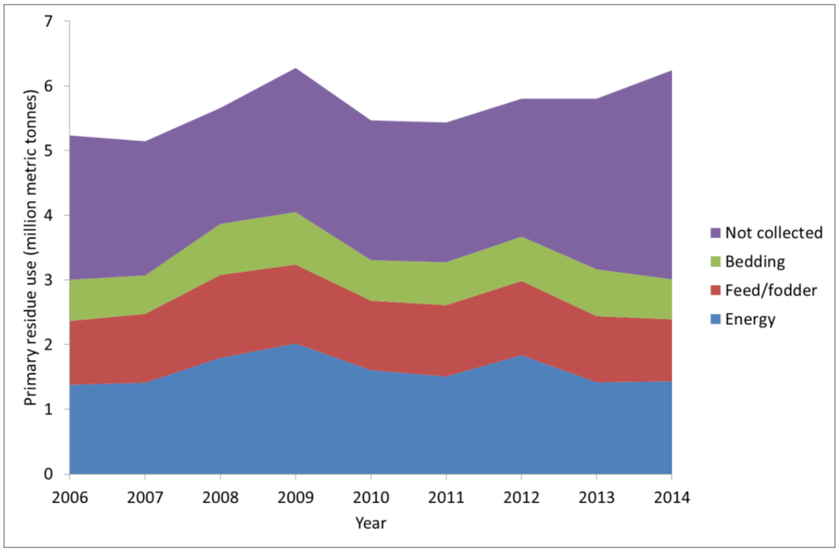


Figure 3.1. Annual production and use of primary crop residues from Danish agriculture (Statistics Denmark 2015).

Canada

The current markets for crop residues are animal bedding, animal feed, and mushroom substrate. Cereal straw supplements forage crops, such as hay and fodder corn. The potential markets for lignocellulosic crop residues include cellulosic biofuels, bio-based sugars and chemicals, biomaterials, and agri-wood pellets. The opportunity for agricultural residues to supply these industrial and energy markets depends on factors such as the cost and properties of the residues, the distance from the processing facilities, the cost of converting residues into bioproducts, the profit potential, to what degree the residue is interchangeable with other lignocellulosic feedstocks, and the existence of a government mandate and/or consumer preference for bioproducts.

3.2.1.3 Large-scale opportunities, distributed networks and niche markets

Parallel to the widespread use of straw for CHP production, Danish companies have been working intensively to develop technologies for converting straw to ethanol and other bioproducts. The Inbicon project established their first pilot plant in Denmark in 2003, followed by a second pilot plant in 2005 and finally a demonstration scale plant in 2009 (Larsen et al. 2012). The demonstration scale plant has a capacity of 4 metric tonnes of straw per hour, and produces, in addition to ethanol, lignin pellets, and vinasse. The latter may be further processed to biogas.

In line with their goals for domestic energy security and greenhouse gas reduction, the production of liquid transport biofuels and value-added bioproducts (e.g., chemicals) presents the largest opportunity for the USA with respect to agricultural residue use in a biorefining context. Currently, the USA is the largest producer of fuel ethanol; producing 14.3 x 10^9 gallons (54 x 10^9 liters) by 2014 (RFA 2015). At this point, fuel ethanol is primarily produced from corn starch. The residual corn fiber, protein, vegetable oil, and minerals are used as distillers dried or wet grains in livestock feed (US DOE

2011). Other agriculture biomass currently used for energy production includes soybean oil and greases for biodiesel, plus municipal solid waste. By 2012, total agricultural biomass use for energy (residues and crops) was 85 million short tons (77 million metric tonnes). It is estimated to level out by 2017 at 103 million short tons (93 million metric tonnes).

In Canada, large scale bioenergy opportunities, such as the conversion of major coal-fired plants to biomass, have focused exclusively on the use of forest biomass. Smaller regional opportunities are being developed for mixed biomass residues that include agricultural residues. The use of agricultural residues for CHP could be feasible in remote settings without access to natural gas and where users rely on propane, electricity or diesel fuel for heating. Crop residues are also used in small amounts as a supplemental feedstock for anaerobic digesters. While this application is growing as the biogas-green energy network expands, it is not envisioned to become a large-scale application.

Further technological developments, such as economical production of bioaviation fuel from lignocellulose and valuation of lignin, could result in future large scale applications. It is estimated that 923 million litres of bioaviation fuel will be required by 2035 for the Canadian biojet industry to achieve carbon neutral growth.

3.2.2 Supply

3.2.2.1 Current biomass supplies

Prior to 1985, in Denmark straw was mainly used to heat individual homes (Figure 3.2). After 1985, straw use shifted towards distributed heat and power production through district heating and CHP. Today, 1.4 million metric tonnes of straw is used for energy, representing 16 % of Denmark’s renewable energy production.

Revisions of the Biomass Agreement in 1997 allowed for more flexibility in biomass sourcing for CHP, beginning a transition towards increased use of wood pellets and chips. Straw is not the best fuel for direct combustion due to high mineral content that can clog and deteriorate heat exchangers and pollution control equipment. The use of straw for CHP has been in decline since 2010, though the market remains significant.

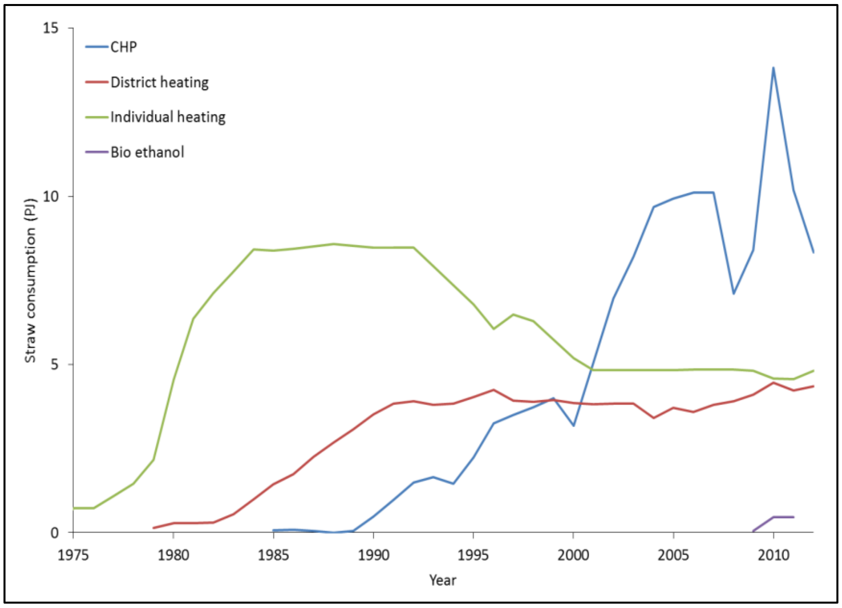


Figure 3.2. Straw used for energy and its allocation to different energy sectors in Denmark from 1975-2012 from Danish Energy Statistics (2015). Data on Danish bioethanol production is not available in national and EU statistics. Here they are calculated from ethanol production statistics from EIA (US Energy Information Administration 2014) assuming a conversion rate from straw to ethanol of 0.27 MJ MJ-1 (Bentsen et al. 2009).

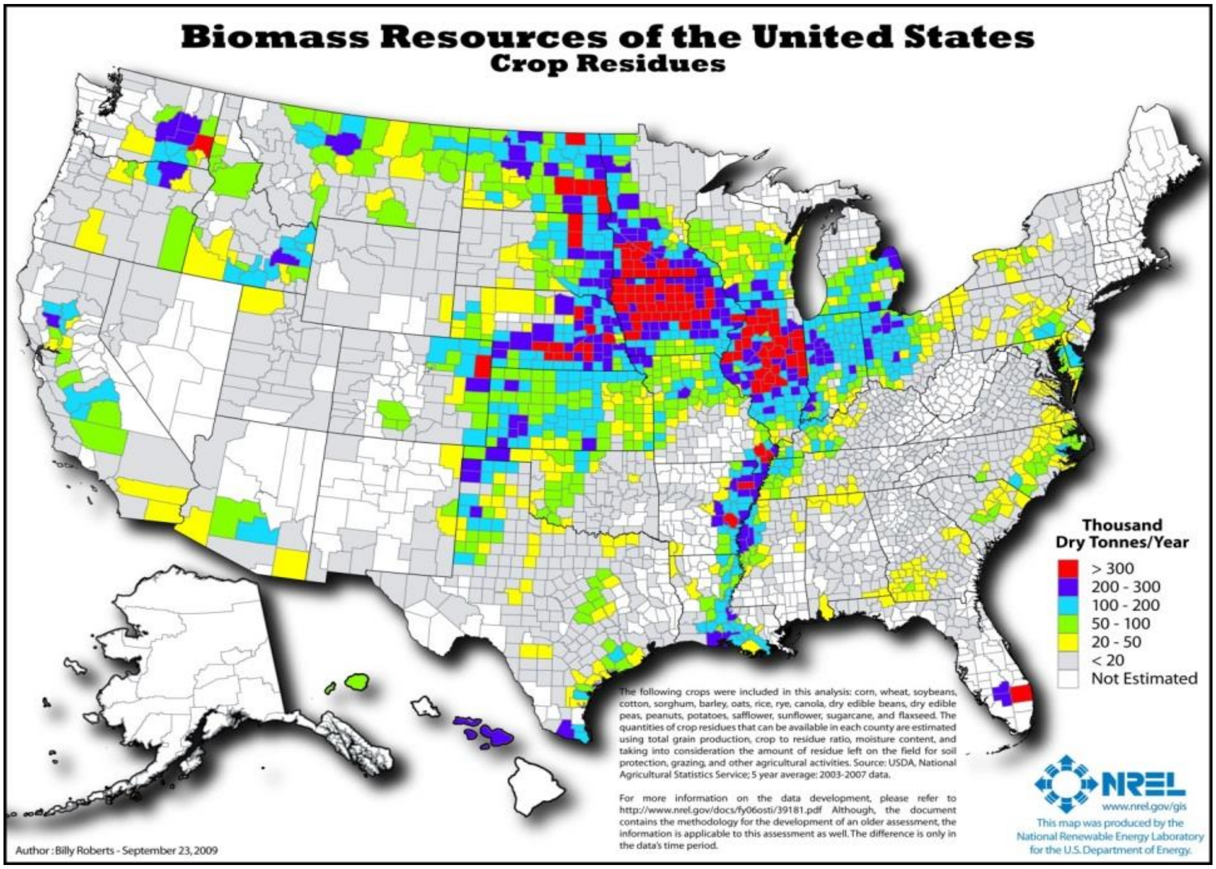
In the USA, agricultural residue collection largely takes place as a side-effect of target crop harvesting. The largest use of agricultural residues is non-energy related at this point and includes applications such as animal feed, bedding, growth media for mushrooms, and erosion control. With the addition of three commercial cellulosic biorefineries in 2014, using corn stover as their primary feedstock, agricultural residue use for energy purposes is bound to increase however.

In Canada, there are no official statistics that track the amount of straw used in animal bedding and feed. The current (2011) appropriation amounts to 3.6 million metric tonnes (dry) for bedding and less than 1 million metric tonnes (dry) for mushroom cultivation and horticultural purposes (Frederic Roy-Vigneault, personal communication, November 19, 2014). An alternative analysis based on livestock numbers for the period 2001 to 2010 estimates an average consumption of 6.9 million metric tonnes (dry) per year (Li et al. 2012). Corn stover residue harvesting is only being carried at small scale to feed pilot and demonstration scale facilities that are testing cellulosic ethanol and sugar processes at pilot scale. No commercial scale facilities using large volumes of agricultural residue for industrial products have been built in Canada as of yet.

3.2.2.2 Technical residue potentials

In Denmark, the +10 million tonnes study (Gylling et al. 2013) estimated that by 2020 the available resource of agricultural residues could increase to approximately 3 million metric tonnes dry matter annually. The increase could be achieved through increased mobilization of existing resources and increased production through cereal variety selection.

The USA production of crop residues is significant. The total annual tonnage from corn, grain sorghum, wheat, barley, oats, and rye exceeds 350 million short tons (318 million metric tonnes) (US DOE 2011). Corn stover consists of about 70% of this total technical potential. Agricultural crop and thus crop residue production is mostly concentrated in the Midwestern parts of the USA (Figure 3.3).



The following crops were included in this analysis: corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, dry edible peas, peanuts, potatoes, safflower, sunflower, sugarcane, and flaxseed. The quantities of crop residues that can be available in each county are estimated using total grain production, crop to residue ratio, moisture content, and taking into consideration the amount of residue left on the field for soil protection, grazing, and other agricultural activities. Source: USDA, National Agricultural Statistics Service; 5 year average: 2003-2007 data.

For more information on the data development, please refer to http://www.nrel.gov/docs/fy06osti/39181.pdf Although, the document contains the methodology for the development of an older assessment, the information is applicable to this assessment as well. The difference is only in the data's time period.

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

Author : Billy Roberts - September 23, 2009

Figure 3.3. Crop residue potential in the Continental United States (NREL 2007). Bioenergy atlas. Retrieved from: (http://maps.nrel.gov/bioenergyatlas).

In Canada, the suitability for agricultural production and hence the potential availability of agriculture residues varies across the country. Li et al. (2012) estimated the total amount of crop residue produced annually over the period 2001-2010 to be 82 million dry metric tonnes. Deduction of the residue needed for soil conservation, livestock bedding and feed requirements reduced the total to 48 million metric tonnes. However, the total amounts can be somewhat misleading. The concentration or density of available biomass is key to determining feedstock costs and financial viability. As shown for four crops in Table 3.1, the concentrations can vary significantly between provinces, indicating that the opportunities should be assessed at a regional or local scale.

3.2.2.3 Economic residue potentials

Bloomberg (2011) estimates that currently in the **EU** it would be profitable to collect 92 million metric tonnes of residues at a delivered gate price of €60 per metric tonne (fresh weight), and projects that 170 million metric tonnes will be available by 2020 at an average cost of €67 per metric tonne. Projection for the availability of various biomass feedstocks in the EU were also made in the Biomass Energy Europe project (http://www.eu-bee.eu/). By 2020, approximately 3 EJ (~200 million metric tonnes) of agricultural residues would be available at a plant gate cost of €3.5/GJ (€51 per metric tonne). Taking into consideration the uncertainty in projecting future supplies at various prices it is estimated that by 2020 170-200 million metric tonnes would be available at a price between €50 and €70 per tonne (delivered at plant gate).

Table 3.1. Estimated average concentration of residues from selected crops from 2001 to 2010 (dry metric tonnes per ha).

Province	Wheat straw	Barley straw	Corn stover	Oat Straw
Prince Edward Island	3.58	2.91	-	3.87
New Brunswick	3.90	3.13	4.44	3.81
Nova Scotia	4.72	2.92	7.08	3.65
Quebec	3.65	3.05	8.00	3.75
Ontario	6.06	3.32	8.58	3.87
Manitoba	4.62	3.22	5.99	4.28
Saskatchewan	3.05	2.62	-	3.59
Alberta	3.78	3.18	6.07	3.90
British Columbia	-	2.74	-	3.78

The US Department of Energy (US DOE 2011) estimated that the 2012 total USA agricultural residue potential ranged between 27 and 111 million short tons (24-101 million metric tonnes) depending on price (US $40-60 per short ton) under baseline assumptions. This potential is expected to increase up to 80-180 million short tons (73-163 million metric tonnes) by 2030 (US DOE 2011) (Table 3.2). Corn stover would equal more than three quarters of this potential. Agricultural processing residues and waste streams would add another 33-51 million short tons (30-46 million metric) by 2012, and between 46 and 84 million short tons (42-76 million metric) by 2030 (depending on price, i.e., US $40-60 per short ton). Under high-yield assumptions, significantly more crop residues could be mobilized. Corn stover alone would almost double from 140 to 271 million short tons (127-246 million metric tonnes) by 2030 at up to US $60 per short ton.

Detailed agricultural residue cost curves are not available for Canada as a whole. Modelling carried out by Kumarappan et al. (2009) showed forest and mill residues to be the most abundant at lower feedstock costs. Significant volumes of agricultural residue become available above US $60 per metric tonne (Table 3.3).

Table 3.2. Summary of baseline and high-yield scenarios — agricultural residues and waste resources (US DOE 2011).

	<$40 per dry ton				<$50 per dry ton				<$60 per dry ton			
Feedstock	2012	2017	2022	2030	2012	2017	2022	2030	2012	2017	2022	2030
						Million dry tons						
Baseline												
Corn	19	32	42	65	73	93	108	129	85	106	120	140
Wheat	6.7	7.8	9.1	12	18	22	26	31	23	26	31	36
Barley, Oats, Sorghum	1.0	1.3	1.6	2.9	2.4	2.5	2.4	3.6	2.8	2.7	2.6	3.7
Total primary residue	**27**	**41**	**52**	**80**	**94**	**117**	**136**	**164**	**111**	**135**	**154**	**180**
Secondary residues & wastes												
Rice field residue	6.5	6.9	7.4	8	6.5	6.9	7.4	8	6.5	6.9	7.4	8
Rice hulls	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7
Cotton field residue	4.2	5.3	5.9	6.7	4.2	5.3	5.9	6.7	4.2	5.3	5.9	6.7
Cotton gin trash	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8
Sugarcane residue	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Orchard and vineyard prunings	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5
Wheat dust	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Animal manures	12	13	16	20	29	34	41	56	30	35	43	59
Animal fats	0	0	0	0	0	0	0	0	0	0	0	0
Total secondary residues & wastes	**33**	**36**	**40**	**46**	**50**	**56**	**65**	**82**	**51**	**58**	**67**	**84**
Total baseline	**59**	**77**	**92**	**126**	**143**	**174**	**201**	**245**	**162**	**192**	**221**	**265**
High-yield scenario												
Corn stover	71	132	157	221	143	200	228	264	153	209	234	271
Wheat Straw	9.8	12	13	16	60	35	38	42	35	39	42	46
Barley, Oats, Sorghum	1.5	1.5	1.4	1.7	3.6	3.4	2.8	3.1	4.0	3.6	2.9	3.0
Total primary residue	**83**	**146**	**171**	**238**	**176**	**239**	**269**	**309**	**193**	**252**	**279**	**320**
Total high-yield	**115**	**182**	**210**	**284**	**226**	**295**	**334**	**391**	**244**	**310**	**346**	**404**

Table 3.3. Biomass supply cost estimates for Canada (in 2008 US$) (Kumarappan et al. 2009).

Biomass price, US$/dry tonne*	Quantity available (million dry tonnes)				
	Municipal solids waste	Agricultural residue	Forest & mill residues	Energy crops	Total**
30	1	6	12		20
40	2	7	12		22
50	3	7	30		40
60	4	31	43		79
70	5	37	43		85
80	6	42	43	26	117
90	7	42	43	30	121
100	7	42	43	31	123

* US$ (2008) at the biorefinery gate
** Total values may differ from summed amounts due to rounding.

In 2008, a major study was undertaken by EcoRessources and Agronovita to determine the logistical costs associated with agricultural residue procurement in Canada. The aim of the study was to identify feedstock types and costs in order to supply 700,000 dry tonnes of agriculture residue to a future advanced biofuel facility. Residue costing included harvesting, storage, transport and a grower's payment. Agricultural residues were estimated to cost (2006-2007 Canadian dollar; ÉcoRessources Consultants and Agronovita Inc. 2008):

- 65 CA$/dry tonne of cereal straw or 0.33 CA$/dry tonne/km in Western Canada; and
- 86 CA$/dry tonne of corn stover or 0.43 CA$ /dry tonne/km in Eastern Canada.

Cost information is more meaningful at the regional or local level. Marchand (2015) recently revised the farm gate cost of corn stover in southwestern Ontario to 54.44 CA$ /tonne stover (at 15.5% moisture). Dr. Jian Gan of Texas A&M modelled the cost of corn stover removal for different soil types in this region. As shown by the preliminary results in Figure 3.4 for the Brookston soil type under conventional tillage and assuming a 1% discount rate, the marginal cost rose dramatically as corn stover removal rates exceeded 25%. The model results indicate that no stover would be harvested at a stover price below US $45 per dry metric tonne. The quantity harvested could reach 800,000 dry metric tonnes annually at the price of US $50 per dry metric tonnes, with a maximum harvest of 2.1 million dry metric tonnes annually at prices over US $75 per dry metric tonnes.

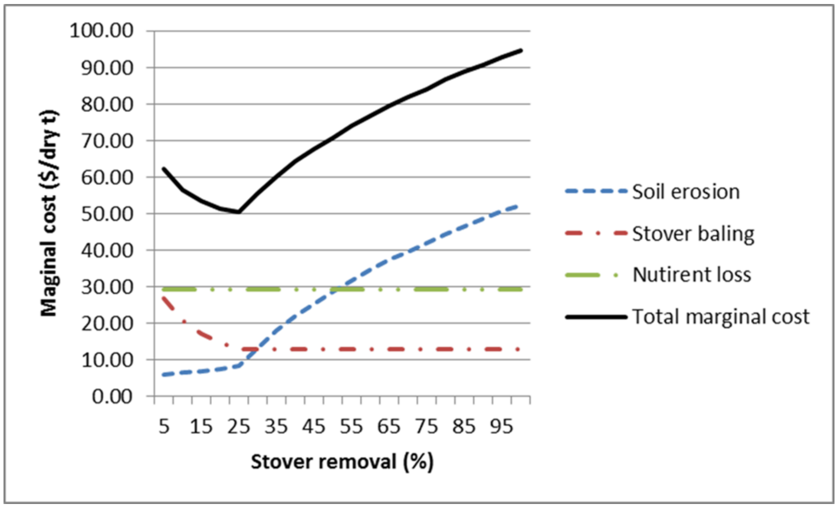


Figure 3.4. Corn stover supply curves for Chatham-Kent, Elgin, Essex, Lambton, Middlesex and Huron counties, Ontario, Canada. (Preliminary results by Dr. Jian Gan, Texas A&M).

3.2.2.4 Summary

Estimates of current use and future availability vary widely as described above and because of these uncertainties estimates should be considered as ranges. Table 3.4 represents projections for the case-study regions Denmark, USA, and Ontario, Canada.

Table 3.4. Estimates of current agricultural residue availability in Denmark, USA, and Canada.

Region	Current harvest for energy purposes	Source
Denmark	1.4 million metric tonnes of straw harvested annually for energy purposes.	Statistics Denmark - statbank.dk 2015
USA	?	
Canada	—	
Region	**Technical/economic potentials**	**Source**
Denmark	3 million metric tonnes (dry matter) by **2020** through increased mobilization of produced straw and increased straw production by cultivar selection.	Gylling et al. 2013
	2.5 million metric tonnes (dry matter) by **2020** through additional straw harvest without the above efforts.	
USA	The **2012** economic agricultural residue potential was estimated to be between 27-111 million short tons (24-101 million metric tonnes) annually depending on price (US $40-60 per short ton).	US DOE 2011
	The vast majority of crop residues are corn stover (77 %), produced largely in the midwestern USA.	Nelson 2002
	2022 crop residue potential of 52-154 million short tons (47-140 million metric tonnes) at US $40-60 per short ton.	US DOE 2011
	2022 agricultural processing residues and waste stream potential of 40-67 million short tons (36-61 million metric tonnes) at US $40-60 per short ton	
Canada	Based on 2001-2010 data, at least 48 million metric tonnes could be available for bioenergy and/or conversion into other bio-products.	(Li et al., 2012)
Ontario, Canada	An estimated 3 million metric tonnes of corn stover and 2 million metric tonnes of wheat straw could be removed for bioenergy or other bioproduct use while maintaining a sustainable soil organic carbon budget.	(Oo 2012)

3.2.3 Economic competitiveness relative to reference energy production systems

Straw is historically the cheapest form of biomass available in **Denmark**, and straw based bioenergy is, as other biomass fuels, exempt from CO_2 taxes, making it competitive with oil and natural gas (Figure 3.5).

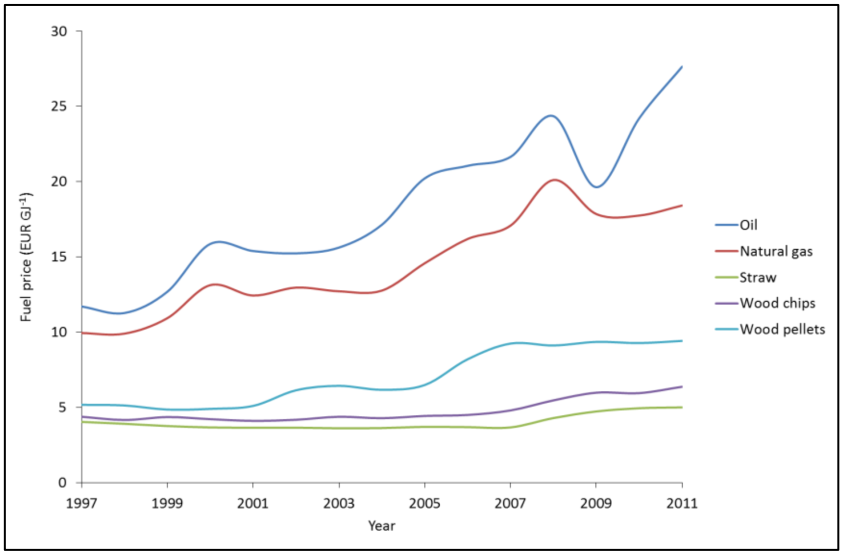


Figure 3.5. Fuel prices including taxes in Denmark for fuels delivered to district heating plants (Dansk Fjernvarme 2012).

The strategic goal of the **US** Department of Energy's Bioenergy Technologies Office (BETO) is to meet a feedstock cost target of US $80 per short ton (US $88 per metric tonne) delivered at the entrance of the conversion facility, including grower payment and logistics, in support of reaching a US $3 per gallon of gasoline equivalent (US $0.79 per liter of gasoline equivalent) delivered fuel target by 2022 (US DOE 2013). Targets are generally iterated between advancements in feedstock logistics and the development of more robust conversion systems. The 2014 average retail gasoline price per gallon (all grades all formulation) at the pump was US $3.44 (US $0.91 per liter) (US EIA 2015).

With respect to heat and power applications, the cost of bioenergy cannot compete with the current price of natural gas in **Canada**. Renewable energy incentives and the monetisation of CO_2 reductions help to improve the financial viability of bioenergy production. Such measures are generally implemented at the provincial level. With respect to transportation fuels, grain-based ethanol needs to derive substantial value from its co-products to be economically viable. In the near term, it is still more economical than ethanol derived from agricultural residues. Both efficiency improvements and co-product valorisation are needed for financial sustainability. For this reason, many 1G biofuel plants are working to develop a higher-value suite of products and become more complex biorefineries.

3.3 OPERATIONAL ANALYSIS

3.3.1 Logistics of current systems

3.3.1.1 Denmark

Straw is baled in the field and transported for intermediate storage at the farm or energy utility. Straw used in larger CHP plants is delivered by road in the form of 500 kg bales. Despite more than 20 years of experience in increasing supply-chain efficiencies, inefficient road transport is still an issue in Denmark. Because of the low density of straw bales, road transportation is volume-constrained and trucks transport only one-third of their load capacity. Development of densified bales has not led to significant breakthrough on the operational level. Recently German machine manufacturer Krone has developed machinery to pelletize straw directly in the field (http://landmaschinen.krone.de) to densify the straw resource and reduce subsequent handling cost. The machine, however, has a must lower capacity than traditional balers.

3.3.1.2 USA

In the USA, the cellulosic biofuel industry relies on a vertically integrated feedstock supply system, often referred to as the “conventional system,” where agricultural residues are procured through contracts with local growers, harvested, locally stored, and delivered in low-density form to the nearby conversion facility. The USA cellulosic biofuel industry is still in its infancy, currently producing less than 1 million gallons of cellulosic ethanol per year, and current practice may not represent that of a fully evolved industry. The conventional system has been demonstrated to work in a local supply context within high-yield regions (e.g., the USA Corn Belt). However, scaling up the biorefinery industry will require increasing feedstock volumes at decreasing costs.

3.3.1.3 Canada

The logistics of harvest, baling, storage, transport, and pre-processing corn stover are currently being evaluated in southwestern Ontario, Canada. This is a particularly promising region of the country with very productive agriculture, excellent transport links, demonstrated innovation capacity, and clusters of related industries and supportive communities. In 2012-2013, grain corn yields averaged 10.67 metric tonnes per hectare (170 bushels per acre) and furnished three ethanol plants and one corn refiner. Work has been underway since 2010 to explore the feasibility of converting agriculture residues (mainly corn stover) and purpose grown crops into cellulosic sugars and other bioproducts.

The objective of the logistics work is to develop a practical scheme for providing a consistent supply of corn stover (or stover blended with wheat straw, switchgrass and Miscanthus) that:

- agriculture producers can implement under a variety of growing scenarios and weather conditions;
- satisfies the quality specifications of processors with minimal losses (or markets for lower quality material);
- arrives at a price point that is profitable and acceptable for all members of the supply chain; and
- does not have a detrimental impact on the following years' crop production.

As shown in Figure 3.6, harvest demonstration trials have been carried out with specialised high-density-baling equipment operating in a two-pass system. A number of harvest practices that have been developed in Iowa in the USA are being reviewed for their applicability in southwestern Ontario. It is critical that feedstock costs are kept low for the bio-processor while still providing sufficient financial incentive for agricultural producers to commit to harvesting a portion of their stover on a long-term basis.

Figure 3.6. Corn stover harvest demonstration at Woodstock Outdoor Farm Show, Sept 2014.

3.3.2 Operational challenges to realizing potential

3.3.2.1 Challenges

There are a number of challenges to realizing the mobilization potential of agricultural residues for bioenergy and biorefining applications, including the following.

- **Feedstock cost:** The cost of delivered agricultural residue can represent close to 50% of the operating cost of a biorefinery.
- **Feedstock (bulk) density:** Unprocessed agricultural residues have relatively low bulk densities, limiting cost-efficient transportation.
- **Economic sustainability:** Residue harvest cannot be allowed to negatively impact the core business of agricultural producers, i.e. production of quality grains and oilseeds for food and feed. Numerous agriculture producers in a given region need sufficient financial incentive and to be convinced that there will be no short- or long-term reduction in the productivity of their land.

- **Environmental sustainability:** Absence of guidelines and best management practices, as well as long term soil studies that provide validation of these practices, on the amount of residue (from what soil type and under what conditions) that must be retained without impacting soil health.

- **Feedstock quality:** Consistent and known feedstock quality is required for applications such as cellulosic ethanol and lignin production. Agricultural biomass is inherently heterogeneous in nature and subject to degradation, making quality subject to variation. Specifications and tolerances must be clear, and markets are needed for off-spec residue. Alternatively, logistic systems including decentralised processing centers are required to homogenise the feedstock chemically and physically, thus also improving storability/stability, bulk/energy density, and flowability, among others.

- **Feedstock availability:** Crop residue availability (in quantity, quality, and cost) is subject to changing biophysical factors. Climate and weather fluctuations can positively and negatively affect yields and impact the timing of harvest. While conventional feedstock supply systems are well adapted to supply biorefineries in local supply context within high biomass yield regions, they could encounter issues in some years due to inclement weather (e.g., drought, flood, heavy moisture during harvest, etc.). These supply uncertainties tend to increase the risk, which could limit the biorefinery concept from being broadly implemented.

- **Market uncertainty:** Biomass supply and demand is subject to changing market factors (e.g. fluctuating markets for primary products such as corn and wheat, competing uses, and prices of alternative raw material). Even in highly productive areas supply and demand and cost and prices can therefore be unpredictable.

- **Framework conditions:** Absence of a stable policy framework for investments, e.g. constant feed-in rates, duration of mandates, valuation of GHG reductions, etc. and dedicated strategies that support new supply chain development.

- **Investment gridlock:** Chicken and egg situation that impedes investment: processors want to build a facility if there is a guaranteed, consistent supply of crop residue while residue providers want a commitment from a processor. Residue processors seek flexibility with respect to feedstock procurement and can appear to be indifferent to the type of feedstock as long as quality and cost specifications are met. On the other hand, agriculture producers need assurances that there will be buyers for their residue before making significant investments.

- **Other:** Barriers typical of an emerging industry including a lack of information, perception of high risk, little commercial experience, need for market acceptance, etc.

Current bioethanol and biorefinery supply chain systems where feedstocks are procured through contracts with local growers, harvested, locally stored and delivered in low-density format to conversion facilities can only partially address these issues. Further optimization of the feedstock supply chain is required.

3.3.2.2 Opportunities to increase supply chain logistical efficiencies and reduce cost of delivered feedstock

Biomass pre-processing can help alleviate a number of the challenges outlined in the previous section. While it initially increases feedstock costs, it eliminates a range of operational uncertainties along the biorefinery supply chain, ultimately resulting in net system benefits (Lamers et al. 2015). Densification, e.g., conventional pelleting, of residues improves homogeneity, stability and storability, bulk and energy density, flowability, and other aspects. This improves transport economics and helps expand the sourcing area, therefore increasing overall residue availability and reducing the risks of fluctuating regional supplies.

In the USA, the advanced uniform feedstock design system (Hess et al. 2009) introduces methods to reduce feedstock volume, price, and quality supply uncertainties via a network of distributed biomass processing centers, so-called depots. Depots use one or several biomass types to generate uniform format feedstock ‘commodities’. These commodities are intermediates with consistent physical and chemical characteristics that meet conversion quality targets and at the same time leverage the spatial and temporal variability in supply volumes and costs by improving flowability, transportability (bulk density), and stability/storability (dry matter loss reduction). A fundamental difference to the existing conventional supply system is that the advanced system emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources (Hess et al. 2009, Searcy and Hess 2010).

3.3.3 Feedstock availability at operational and whole supply chain scales

Technical availability of feedstock does not necessarily equal availability at the operational level. The availability of agricultural residues for bioenergy and biorefining is site-specific and highly influenced by a number of complex biophysical and socioeconomic factors that range from the local (farm) scale to the national scale (Table 3.5) (Gan and Smith 2012).

Table 3.5. Political, economic, and biophysical factors affecting residue availability at an operational level.

Political and economic factors

Factor	Implications
World grain markets	World grain markets will influence the amount of land under cultivation for grain crop (+/-) as well as the genetic modification of plants to increase grain yields (e.g., efforts to increase grain-to-stover ratio) (Bentsen et al. 2014). Because residues are co-products of grain production, these changes will influence theoretical residue availability either positively or negatively.
Costs of delivered residues	Fuel production and delivery must be cost-competitive for energy producers, compared to alternative fuels. Competitive prices will attract energy producers to agricultural residues as a feedstock source, increasing overall demand. Increased demand will in turn encourage more farmers to make a portion of their residues available for bioenergy and biorefining application.
Competing demands	Depending on current market prices and the availability of hay and forage crops, farmers may choose to sell their residues to competing users such as animal bedding, reducing residue availability for bioenergy and biorefining.
Fit of residue harvest into farming operations	Depending on crop prices, the type of crop rotation, crop yields, the availability of residue harvesting equipment and length of harvest season, residue harvest may or may not be practically or financially feasible for producers in a given area.
Cost of nutrient replacement	Nutrients contained in the residue will be removed from the field, and not be available for the following crop. The amount of nutrients to be replaced (purchased) will depend on the crop rotation and soil nutrient levels. Additional soil testing could be required.
Benefits to the producer/willingness to remove residues for bioenergy and biorefining	Depending on the business model adopted, the benefits of using agricultural residues for bioenergy and biorefining could accrue further along the supply chain and not at the producer level, meaning that without transfer payments or other incentives producers may choose not to harvest their residues for bioenergy and biorefining, significantly reducing residue availability at the operational level (Gan and Smith 2012).

Biophysical factors affecting operational availability

Factor	Implications
Environmental conditions of site (e.g., soils, slope)	Residue availability can vary greatly from site to site depending on site conditions. In areas with low organic carbon or high slopes, for example, a higher proportion of residues will need to be maintained on site to protect soil fertility and site productivity and prevent erosion. Reflecting this variability in higher-level estimates of current and future availability is difficult.
Variability in climate and weather	Residue availability can vary greatly from year to year depending on climate and weather conditions, for example: ➢ Extreme weather can reduce crop growth and residue availability. ➢ The window for residue removal can be drastically reduced if for example winter arrives early and fields need to be prepared for the next crop cycle. ➢ Heavy rains during harvest can limit accessibility and reduce residue storability.

3.4 SUSTAINABILITY ANALYSIS

Feedstock supply chains need to be logistically viable, profitable for agriculture producers and affordable for downstream processors. They need to be sustainable from economic, environmental and social perspectives, and be converted into products that are better than what currently exists to justify the cost of change. A number of frameworks exist to assess the three dimensions of sustainability, including GBEP (Global BioEnergy Partnership), LEAF (Landscape Environmental Assessment Framework), PROSUITE (PROspective SUstainability Assessment of Technologies), and LEEAFF (Land Use, Environment, Employment, Acceptance, Financial, Feedstock).There are significant commonalities between these systems. That is, they use many of the same criteria to evaluate sustainability, but the specific indicators and metrics used to assess the criteria vary. GBEP, LEAF and PROSUITE use quantitative indicators, while LEAAFF can be used in a quantitative or qualitative manner as a screening tool. These systems provide similar information on sustainability, but have different formats for communication with users.

3.4.1. Sustainability indicator analysis of supply chain — Elaboration of indicator sets analyzed generally: social, environmental, economic, and potential trade-offs among sustainability considerations

3.4.1.1 Denmark

In the Danish case, the GBEP framework was used to evaluate environmental, social and economic sustainability of two supply chains, straw for combined heat and power production and straw for bioethanol production. A subset of indicators was selected based on relevance and data availability, and unfortunately the social pillar was poorly addressed because of lack of data. An overview of findings of the Danish case is presented in Table 3.6.

As the GBEP framework does not identify threshold values for the individual indicators, the analysis cannot determine whether specific supply chains could be considered sustainable or not. It can, however point to critical issues that need attention or improvement. For the case of residue use in Denmark the critical environmental issue is the development in soil carbon caused by residue harvest.

Table 3.6. Summary of GBEP indicator values for the reference year 2000 and developments to 2012.

Indi-cator	Name	Unit	Ref. year	Straw to CHP			Straw to EtOH		
				Value	Change	Change /yr	Value	Change	Change /yr
1	GHG emissions	g CO_2eq/MJ_{el}	~2010	97					
		g CO_2eq/MJ_{EtOH}	2008				202		
2	Soil quality	%	2011-12	34			0.0		
4	Non-GHG emissions, supply chain	mg SO2/MJel	2010	100-170					
		mg NOx/MJel	2010	310-530					
		mg PM10/MJel	2010	530					
		mg PM2.5/MJel	2010	410					
7.1-3	Biological diversity	Ha	2000	0					
			2012	0	-	-	0	-	-
		%	2000	0			0		
			2012	0	-	-	0	-	-
11	Change in income	EUR/tonne straw	2012	11-21.3					
17.1	Feedstock productivity	t/ha/yr	2000	3.8			3.8		
			2012	3.9	ns	ns	3.9	ns	ns
17.2	Processing productivity by mass	MJ_{el}/t	2000	4,495					
			2010	5,365	870	79			
		MJ_{total}/t	2000	13,050					
			2010	13,340	290	26			
		MJ_{EtOH}/t	2010				4,000		
17.3	Processing productivity by area	MJ_{el}/ha	2000	16,811					
			2010	20,065	3,254	296			
		MJ_{total}/ha	2000	48,807					
			2010	49,892	1,085	99			
		MJ_{EtOH}/ha	2010				14,960		
17.4	Production cost	EUR/lit.	2010				0.9		
18.2	Net energy balance	Ratio (0-1)	2000	0.995			0.995		
			2012	0.995	0	0	0.995	0	0
18.3	CHP, electricity		2000	0.31					
			2010	0.37	0.06	0.005			
	CHP, total		2000	0.90					
			2010	0.92	0.02	0.002			
	EtOH, total (C6)		2010				0.71		
18.4	CHP electricity		2010	0.94					
	EtOH, C6		2005				0.74		
	EtOH, C6		2010				0.11		
22	Energy diversity	Index (0-1)	2000	0.0037			0		
			2012	0.0105	0.0068	5.23E-04	0.0009	0.0009	6.92E-05

3.4.1.2 USA

The US Department of Energy's Bioenergy Technology Office through Idaho National Laboratory developed an integrated data management and modelling framework known as LEAF to perform biomass sustainability assessments and develop production system design concepts. The integrated modelling framework has been used to perform peer-reviewed assessments from the sub-field (<10 meter) to national scale (Muth et al. 2012, Muth and Bryden 2013, Muth et al. 2013, Bonner et al. 2014). LEAF is a decision support platform that actively improves with progressive decisions using known status of land to determine the multi-factor environmental performance of agricultural production landscape designs. Many models are available to evaluate environmental performance parameters. The challenge of these multiple, varied models is that they are typically designed to consider a limited subset of parameters, and they often operate at different spatial and temporal scales, and may not be applicable across all regions and agronomic land management systems. LEAF overcomes these challenges and unifies these varied models into an effective, single computational platform, to provide decision makers with reliable, site-specific environmental performance assessments (Abodeely et al. 2012, Muth and Bryden 2013).

The LEAF sub-field decision support analytics is a computational strategy that uses data inputs from multiple spatial scales to investigate how variability within individual fields can impact sustainable residue removal for bioenergy production. Increased availability of sub-field scale datasets such as grain yield data, high-fidelity digital elevation models, and soil characteristic data provides an opportunity to investigate the impacts of sub-field scale variability on sustainable agricultural residue removal and bioenergy crop production (Muth 2014, Bonner et al. 2015).

3.4.1.3 Canada

The sustainability assessment work began by reviewing the GBEP framework to assess whether it might inform and facilitate the design of a new agricultural residue supply chain in Southwestern Ontario. The assessment completed by Ontario Federation of Agriculture, La Coop fédérée and Agriculture and Agri-Food Canada in October 2013 found some of the GBEP indicators were not relevant, and application would have to take place at a much smaller scope than national because of the large size of the country. Also, many of the GBEP indicators apply to "land on which bioenergy is produced", which does not exist in Canada. In this case, agriculture residues are grown as a by-product on agricultural land, and it would follow that this material would have to comply with sustainability requirements of grain production.

As separate work, this group followed the development of the international standard ISO 13065 on Sustainability Criteria for Bioenergy with the hopes that this standard could provide a useful framework. The final product is a type of management standard that guides users on what sustainability indicators should be identified and addressed with a management plan. The principles, criteria and indicators provide high level guidance, but not the direction needed to make design decisions.

The EU's FP7 framework supported a very ambitious integrated sustainability assessment project called PROSUITE. The development of this tool and its application to bio-based projects was followed to determine if it could be applied for the Canadian regional case study. PROSUITE builds on a life cycle approach, and brings together many sustainability indicators for an integrated assessment and discussion of trade-offs. It requires a fairly specific, quantified understanding of the new technology as well as of a reference system that is used for comparison. Details on the corn stover to bio-chemicals process were however not available.

As the case study was of a prospective value chain, the LEEAFF framework (used in qualitative mode) was found to be the most practical tool to provide a holistic view of the corn stover to bio-chemicals and bioenergy value chain under consideration. The framework questions are the questions most frequently heard when discussing new project development with stakeholders. Many of the LEEAFF sustainability indicators are the same as those of other frameworks. It was used as a screening tool to show what is known and not yet known, and the areas to which attention should be paid in the development process (Table 3.7).

3.4.2 Governance

By-products from agricultural crop production are subject to the same sustainability requirements as are the main crops. However, additional economic and social opportunities arise, together with environmental concerns when crop residues are harvested. The latter includes issues related to the soil, for example conservation of soil organic matter and nutrients, water erosion and runoff, wind erosion, and soil moisture.

3.4.2.1 Regulation in the agricultural sector

In the **EU** the cross-compliance principles of the Common Agricultural Policy (CAP) were introduced in 2003. Cross-compliance is a mechanism that links agricultural subsidies with the farmers' compliance with basic standards concerning the environment, food safety, animal and plant health, animal welfare, and maintaining land in good agricultural and environmental condition (EC 2015). It varies among member states in which form the requirements have been implemented; in Denmark 105 requirements have been formulated under the cross-compliance requirements (Ministeriet for Fødevarer, Landbrug og Fiskeri, 2015).

Except for straw recommended as an option for mandatory bedding in animal farming, only one of the EU cross-compliance requirement concerns straw in prohibiting its burning in open fields. The requirement contributes to meeting overall criteria as protection against soil erosion, and maintenance of soil organic matter and soil structure. In Canada excess crop residues can be burnt to facilitate seeding, provided strict guidelines are followed, with this being the exception rather than the rule. As in Europe, residues are usually chopped and ploughed into the soil.

Agricultural producers in the USA generally are subject to only few mandatory conservation measures (Endres 2011), but agricultural policies do include incentives to set aside lands for conservation purposes. *The Conservation Reserve Program* (CRP), established by the 1985 Farm Bill, is the largest conservation program in the USA by acreage and expenditure. Later programs focus more on conservation through management practices, and it has become an option to participate in "working lands" environmental enhancement programs such as the *Conservation Security Program*, The *Environmental Quality Incentives Program*, and the *Agricultural Management Assistance*. Other such programs have existed, for example *The Wildlife Habitat Incentives Program* (WHIP), which was repealed in 2014, with parts of its contents rolled into EQIP.

In **Canada**, agri-environmental performance is tracked on a five year basis for agricultural land in all provinces (Eilers et al 2010). Fifteen indicators, covering farm land management, soil health, water quality and air quality, are used to show temporal trends and risk of environmental damage. Provincial and federal environmental regulations related to waterways, pesticide application, etc. must be adhered to. Beyond this, agriculture producers are encouraged to have environmental farm plans that identify their specific environmental risks and outline their mitigation plan. Rising interest from consumers and food processors has led the agriculture industry to establish the Canadian Roundtable for Sustainable Beef and Canadian Roundtable for Sustainable Crops which are endeavouring to develop a practical framework for sustainable agriculture.

Table 3.7. LEEAFF Sustainability Framework: Corn stover to bioproducts value chain

Impact Category	Description	Evaluation of Partial Corn Stover Harvest for Production of Bio-chemicals and Bioenergy
Land Use	Issues related to the land used for biomass feedstock production including land ownership, historical land use and land use change, current land use conflicts, land use efficiency, and broader context questions such as food security.	Use of existing agricultural land for feedstock production; Increased land use efficiency; No land use change is anticipated; Expansion of corn acreages (on existing ag land) is possible in the eastern Canada clay belt and in the crop-growing areas of the Prairie provinces.
Environment	Environmental impacts related to feedstock production and product including greenhouse gas emissions, air emissions, water emissions, soil sustainability, biodiversity Environmental benefits: carbon sequestration, remediation	Fewer GHG emissions are released from ethanol derived from corn stover when compared with grain-derived ethanol (Tools: GHGenius, HOLOS) Potential issues: • Loss of Soil organic matter, soil organic carbon • Loss of nutrients (N, P, K) • Soil Compaction • Additional Air Emissions (PM)
Employment	Issues related to all stages of the product lifecycle including job creation or retention, job type, wages, educational requirements, new skills development, employment equity	Additional employment is expected to occur in construction (temporary), manufacturing, transportation and agricultural sectors. Rural part time employment (off farm employment)
Acceptability	Acceptability by all stages of the lifecycle including the company (internal), community, intra-industry, inter-industry, public	Producer – YES - if it fits with farming operations; if it does not impact core business - production for food and feed markets; if it does not affect long term soil productivity ENGOs – Y or N; potential concern for soil erosion, long term soil productivity, biodiversity *(need to demonstrate safeguards)* Public – Expect Y; preference for use of non-food biomass and no land use change;
Financial	Information on size of investment, operating costs, profitability and return on investment, projected markets for biorefinery products, government mandates, incentives & subsidies, tax revenues	Producer – potential for additional net revenue associated with stover removal *Do all co-products have markets?* *Monetisation of GHG reduction?* *Availability of incentives?*
Feedstock	Renewable and non-renewable resource use including biomass, water, energy and chemicals; supply and cost information	Sufficient volumes for biorefinery are available, with a good buffer *Logistic requirements - collection, storage, and transport for 250,000 dry tonnes?* *Feedstock quality requirements for different users?*

3.4.2.2 Best management practices in the agricultural sector

In **Denmark** the extension services provide comprehensive information and advice on handling, logistics and economy of straw harvest (Danske Halmleverandører 2015). They also inform and advice about possible impacts on soil carbon contents, although Best Management Practice guidelines (BMPs) have not been established. The basis for guidance to farmers is the so-called Dexter-index (the ratio between clay and soil carbon), which has been suggested as a way to assess when and where soil carbon contents are critical to maintenance of appropriate soil physical properties (Dexter et al. 2008, Schjørring et al. 2010).

Comprehensive BMPs for management of crop production have been elaborated in the **USA** and **Canada** by universities, extension services, and government bodies, such as the US Department of Agriculture (USDA). BMPs commonly address residue management as a measure of soil conservation (e.g. USDA NRCS and University of Wisconsin–Extension, Government of Alberta, Agricultural and Forestry 2004). As a new practice, partial residue removal for bioenergy or bio-products production requires agreed-upon BMPs or harvest protocols. A number of guidelines are emerging to support participation in the stover supply chains in Iowa and Kansas (Ertl, 2013). In Canada, research and field trial results are contributing to the development of interim guidelines for corn producers who are considering stover harvest.

Compensational measures are also addressed in guidance to farmers, both in **Denmark** and **North America**. Such measures include addition of organic matter with manure (Christensen 2002), even if this cannot reduce evaporation and trap snow like crop residues (Wortmann et al. 2012, Neary 2015). Another mitigation measure is the use of cover crops that can also compensate carbon removals, improve water management and act to protect the soil against erosion and damage to soil structure (Christensen 2002, Wortmann et al. 2012, Neary 2015.

The European Bioeconomy Panel and the Standing Committee on Agricultural Research Strategic Working Group (EBP/SCAR 2014) generally considers that adoption of existing and new innovative best practices around the world has huge potential to increase productivity and thus the biomass supply, without increasing the demand for land. In this regard, crop residue harvesting may be a low-hanging fruit, if scientifically and practically sound BMPs for efficient and sustainable harvesting can be established.

3.4.2.3 Regulation in the bioenergy sector

Apart from agricultural regulation, sustainability requirements are emerging in energy regulation. The **UK** was first in establishing a regulatory scheme that requires carbon and non-carbon sustainability of transportation biofuels (Renewable Transport Fuels Obligation), electricity and heat (Renewables Obligation, and Domestic and Non-domestic Renewable Heat Incentive (OFGEM 2015). The environmental principles and criteria of the RTFO include ecosystem carbon conservation (above and below ground stocks), biodiversity and soil conservation, sustainable water use, and air quality, while the social principles include workers' and land rights.

The **EU** followed with the Renewable Energy Directive in 2009 (EU 2009), which includes sustainability criteria for liquid biofuels. These criteria address greenhouse gas emission (GHG) savings, biodiversity and prohibition of conversion of land with high carbon stocks, and compliance with cross-compliance requirements of CAP. Similar to the cross-compliance principles from agriculture, energy producers receive subsidies only if they show compliance with sustainability criteria/conservation requirements.

In **EU**, the documentation of sustainability criteria being met relies on a meta-standard approach, where various verification measures can be used, sometimes in combination. The exact requirements for verification depend on the specific legislation, but may include reporting GHG balance using provided calculation tools, private certification, or similar documentation assessed from case to case (see e.g. Endres 2010, Stupak et al. 2015, Mansoor et al. 2015).

Energy from crop residues relatively easily meet threshold values for GHG emission reductions (21–58% for cereal straw), but there are critics (Whittaker et al. 2014) that current methodologies of the EU Renewable Energy Directive, do not account for impacts on soil carbon stocks, and that this may shift emission reductions from positive to highly negative.

In the **USA**, the Renewable Fuels Standard (RFS) mandates that transportation fuel sold in the USA contains a minimum volume of renewable fuel. RFS include minimum threshold requirements for GHG emission reductions, but no non-carbon requirements (EPA 2015, Endres 2010).

3.4.2.4 Barriers to regulation of bioenergy and the bio-economy

Bioenergy production concerns land use, energy, transportation and environment sectors, but in most countries regulation and ministerial responsibilities for these sectors are carried out by separate departments with specific mandates. With the increasing emergence or shift to the use of crop residues in integrated and cascading production of various biomaterials, biochemicals and different bioenergy forms, even more sectors and government departments become involved. The regulation of these new bio-economic value chains becomes highly complex, with relevance and probably overlap of existing regulation from different sectors (SCAR 2014, Det Nationale Bioøkonomipanel 2014). This increases the need for comprehensive coordination among sectors and the associated ministerial responsibilities. Sometimes the regulation of one sector might unintentionally prevent policy goals from being achieved in another sector.

A survey in **Denmark** (Naturerhvervstyrelsen 2015) identified such regulatory barriers, including application requirements when introducing new technologies, and found that classification of residue/waste products might hinder new uses, including use of waste products for soil amendment. Barriers in energy legislation includes the absence of mandated use of advanced biofuels, with the National Bioeconomy Panel recommending a mandated blending requirement of 2.5%, valid until 2030, to kick-off a hesitant bio-refining industry, that is currently seeking to develop their business potentials in other countries. Other legislation with strict requirements on organization and municipal participation in heat production projects furthermore makes it difficult to obtain loans for investments with state or municipalities guarantees. These kinds of challenges are likely to exist also in other countries.

The verification of biomass sustainability continues to be a challenge (Stupak et al. 2015, Mansoor et al. 2015). The European Bioeconomy Panel and the Standing Committee on Agricultural Research Strategic Working Group recognise the value of existing regulation and certification systems to document sustainability of the biomass, but also consider that creating more of the same may not be the best way forward (EBP/SCAR 2014). In line with approaches being developed e.g. by the U.K. and the *Sustainable Biomass Partnership* (SBP), they propose that a system for issuing certificates of origin from so-called *Sustainable Biomass Regions* be established. They consider that a regional/urban approach may be more useful for further promoting and ensuring sustainable forestry, agriculture and marine/aquatic practices. Like others, they suggest that the approach can reduce costs and administrative complexity and ease commitment of primary producers, while at the same time being able to account for shifts in demand and divergent natural or social circumstances and needs.

3.5 SYNTHESIS

3.5.1 Constraints and barriers

3.5.1.1 Constraints on supply, including biomass availability and land-use considerations

Agricultural residues are by-products of existing production and so do not require additional land to produce, unlike many other sources of biomass under consideration for bioenergy and biorefining applications. There are no direct land-use issues associated with their harvest. However, as discussed in previous sections, residue availability is linked to many complex and dynamic factors and is inherently difficult to estimate. The following factors all represent potential constraints on supply:

- World grain market fluctuations
- Biophysical limitations (e.g., extreme weather events)
- Sustainability considerations (e.g., soil fertility and erosion control)
- Competing uses
- Distance to processing plants and inefficient transport restricting location of supply regions
- Uneven benefit distribution along the supply chain
- Lack of incentives for producers to harvest residues

3.5.1.2 Barriers to mobilization

Denmark

Cost: High feedstock costs are a main challenge to diversifying straw use for biorefining in Denmark (Jorgensen 2013). Straw is already extensively used in CHP, and with its low bulk density and high transportation costs competition from emerging supply regions is limited. With a strong market and limited suppliers, costs as high as 550 DKK (~80 USD) metric tonnes^{-1} are not uncommon.

Fuel quality: There are technical issues associated with straw use in CHP, including a high ash and mineral content that can cause corrosion of super heaters, slagging and fouling as well as deterioration of catalysts for NOx reduction. It is therefore a political challenge to encourage fuel ssource flexibility and the use of wood and other sources of biomass for CHP production in Denmark. According to the Biorefining Alliance (2012), a rapid shift to second generation biofuels will only be possible if Denmark institutes a mandatory blend to encourage supply chain development.

USA

Feedstock availability: The cellulosic biofuel industry is projected to be primarily rooted in specific regions with concentrated resource supplies (e.g., high corn producing areas of the Midwest). Outside of these regions biorefineries are destined to be small because of prohibitive feedstock costs and risks.

Feedstock quality: Current, conventional feedstock supply chain systems can only address feedstock quality indirectly through passive controls, e.g., resource selection and best management practices. With an increase in feedstock demand and competition, this will be a limiting factor for a continuous supply (Kenney et al. 2014).

Economics and project finance: Investments in second generation biofuels are still considered risky. Profitability depends on a number of issues including ethanol demand prices and production costs, which are in turn heavily influenced by the technical barriers described below.

Technical barriers: With an anticipated increase in vehicle fuel efficiency and an increase in electrically powered vehicles, it is likely that fuel ethanol sales will hit a blend wall, where blends in excess of 10 % will be required to meet the production mandates set out in the RFS2.

Ontario, Canada

Competing fuels: Using agricultural residues for biorefining is an industry still very much in its infancy in Ontario. Affordable domestic energy sources such as natural gas and an abundance of woody biomass are all barriers to the development of bioenergy supply chains based on agricultural feedstocks. The focus in Ontario is therefore on chemicals and higher value products.

Market development: Ontario currently faces a chicken-and-egg situation that may limit the growth of a biorefinery industry in the province; without reliable markets farmers, will not harvest their residues, and without a reliable source of biomass, investors will not take the risk.

Lack of information: Other barriers typical of an emerging industry include a lack of information on such things as profit margins, market prospects, and how much residue to leave on different soil types to maintain long-term soil productivity.

3.5.2 Solutions for supporting the mobilization of sustainable agricultural residue chains in different operational environments

Large-scale residue removal needs to make economic sense, be environmentally sustainable and fit with the agricultural practices in a given area. The establishment of an agricultural residue supply chain that meets the criteria of diverse clients will require the following.

- A consistent and stable policy framework that supports bioenergy and products made from renewable biomass and wastes.
- The availability of credible and transparent knowledge on processes, costs and sustainability aspects (e.g., for farmers, energy producers and other stakeholders along the supply chain).
- Long-term contracts to increase stakeholder confidence.
- Incentives for farmers to bear the initial investment risk (e.g., subsidies or credits for GHG offsets and energy security enhancements).
- Tools to provide confidence to processors of consistent biomass supply.
- Best management practices for a variety of soil types and operating conditions that ensure removal is not detrimental to soil health over the long term.
- Credible sustainability guidelines.

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4

Biogas Supply Chain

4.1 INTRODUCTION

Many studies have identified agricultural, industrial and household biomass residues as promising bioenergy feedstocks that pose fewer risks with respect to competition for food or environmental effects. The amount of residues available for energy production, the way in which they should be converted, and the organization of emerging bioenergy chains remain the subjects of debate.

Biomass residues may originate from agriculture, industrial production processes or from consumption wastes. Following the definition provided in Chapter 3 (Agricultural Crop Residues), they may be classified as primary residues originating from fields (e.g., straw, leaves, and stover), secondary residues originating from industrial processing (e.g., pits, shells, peels, slaughtering waste and effluents) and tertiary residues from traders, transporters, households, and other actors along production chains involving use of biomass. It is estimated that globally some 5 billion (10^9 basis) metric tonnes of agricultural waste are generated every year; this is equivalent to approximately 1.2 billion tonnes of oil (UNEP 2012).

Converting biomass residues into energy has environmental, social and economic benefits. Agricultural crop residues can be converted to energy through direct combustion (see Chapter 3. Agricultural Residues Supply Chain), or they can be processed into storable fuels such as biogas. Biogas is the final product of a process of anaerobic fermentation (digestion), in which organic material is converted by micro-organisms into methane (CH_4) and carbon dioxide (CO_2) plus residues and by-products under oxygen-free conditions. The overall anaerobic digestion process can be depicted as follows.

$$\text{Organic matter} \rightarrow CH_4 + CO_2 + \text{water} + \text{minerals} + \text{microbial biomass} + \text{organic residue}$$

Methane and carbon dioxide together comprise what is referred to as "biogas." The major minerals produced are ammonium, phosphate salts, and hydrogen sulphide. The solution remaining after digestion, including the inorganic and organic residue, is referred to as digestate, which can be applied to land and is considered an organic fertiliser.

The biogas can be produced in three different temperature regimes: relatively cool (<30^0C, psychrophilic), moderate (30-40^0C, mesophilic), or relatively hot (40-50^0C, thermophilic). Anaerobic bacteria are active in mesophilic and thermophilic temperature ranges, which therefore provide higher biogas yields. For the process to be effective, the C:N ratio should be around 20–30 (Arshadi and Sellstedt 2008).

This chapter discusses biogas production from three locally and globally significant production chains: municipal solid waste (MSW), oil palm residues and co-digestion (e.g. where crop residues are added to manure wastewater digesters to improve biogas production efficiency).

The global production of biogas is growing, and huge unutilized potentials have been reported (e.g., Yu et al. 2010). Anaerobic digestion (AD) installations provide cheap, decentralized energy from waste materials and residues. In China, AD development traditionally played a role in rural development policies (Gregory 2010, Cheng et al. 2014), and construction of household (small farm) digesters is part of development programs in Africa (AfricaBiogas 2015, SNV 2009), Asia and Latin America. The number of biogas installations in use is estimated at more than 35 million, with most being household installations located in China and India (Table 4.1). Large farm digesters and industrial installations are mostly found in Europe and North America.

Table 4.1. The number of biogas installations found in selected studies.

Region	Number of installations (year)	Reference
Europe		
Austria	337 (2013)	Persson and Baxter 2015
Denmark	154 (2012)	Persson and Baxter 2015
Germany	7,850 (2013)	FNR 2015
Netherlands	252 (2013)	Persson and Baxter 2015
Sweden	264 (2013)	Persson and Baxter 2015
UK	634 (2013)	Persson and Baxter 2015
Asia		
China	30 million (2010)	Household digesters; Gregory 2010
India	4.2 million (2011)	Cheng et al. 2014
Nepal	1.3 million (2012)	Cheng et al. 2014
Pakistan	5,360 (2008)	Wikipedia 2015
South Korea	82 (2013)	Persson and Baxter 2015
Viet-Nam	23,300 (2012)	Rajendran et al. 2012
Americas		
United States	2,116 (2014)	Including 239 farm digesters; USDA, EPA and DOE 2014
Brazil	25 (2014)	Connected to the grid; Persson and Baxter 2014
Africa		
Burkina Faso	3,500 (2015)	AfricaBiogas 2015
Ethiopia	10,109 (2015)	AfricaBiogas 2015
Kenya	14,112 (2015)	AfricaBiogas 2015

4.2 MUNICIPAL SOLID WASTE (MSW)

4.2.1 Feedstock supply

Municipal solid waste is an important bioenergy feedstock (IFA 2000). On a global scale, urbanization will lead to an increase in waste generation. Rural communities have fewer packaged products, less food waste, and less manufacturing. A city resident consequently generates twice as much waste as his rural counterpart of equal affluence. As urban citizens are generally more affluent, they generate four times as much waste (United Nations 2014).

The biodegradable fraction of MSW in the **European Union** amounts to 100 million tonnes. The amount of bio-waste can be calculated at some 91 million tonnes (104 million tonnes in 35 European countries). This is comparable to the amount of bio-waste estimated by the European Commission: 118 to 138 million tonnes of bio-waste, of which 88 million tonnes is municipal waste (COM 2010).

Approximately 36% of the bio-waste is composted or digested; a 9:1 ratio of composting to digestion is assumed. Potential biogas production (assuming utilization of all bio-waste at 85 m^3/tonne bio-waste and 55% methane) is 8.8 billion Nm^3 with an energy content of 182 PJ.

MSW production in the **United States** is 389 million tonnes (2008). Management strategies include composting/mulch production (6%), recycling (paper, metal, glass, plastic) (18%), waste-to-energy (7%), and disposal in landfill (69%). Composted MSW amounts to 24.5 million tonnes. No differentiation of data for bio-waste being digested was found.

Global solid waste production is rapidly rising. The world population (7.2 billion in 2013) is projected to reach 8.1 billion in 2025, and to increase to 9.6 billion in 2050 and 10.9 billion by 2100 (United Nations 2013). Much of the demographic change will take place in less developed regions. Collectively, these regions will grow 58% over 50 years, as opposed to 2% for more developed regions.

Currently, 54% of the population resides in urban areas. By 2050, 66% is projected to be urban (United Nations 2014). In 1900, 220 million urban residents produced less than 300,000 tonnes of waste. By 2000, 2.9 billion urban people generated more than 3 million tonnes of solid waste per day (about 1.3 billion tonnes per year). By 2025 this rate will be doubled (Hoornweg et al. 2013), and by 2050 grow to 8 million tonnes per day (3 billion tonnes per year).

The highest rates of increase in MSW are found in China, East Asia, Eastern Europe, and the Middle East. Current global MSW production, 1.3 billion tonnes per year, is expected to increase to 2.2 billion tonnes by 2025 (World Bank 2012); about 560 million tonnes is of organic origin. The biogas potential is 48 million Nm^3 or 1.0 EJ. By 2025, 6 billion (10^9) tonnes of urban waste will contain 1 billion tonnes organic waste with a biogas potential of 86 million Nm^3 (equivalent to 1.8 EJ).

4.2.2 Treatment options

Green waste collection schemes function successfully in many countries. Kitchen waste is often collected and treated as part of mixed municipal solid waste (MSW). Separate collection can divert easily biodegradable waste from landfills, enhancing the calorific value of the remaining MSW and generating a clean bio-waste fraction suitable for the production of high-quality compost and biogas. Effective bio-waste collection may also support recycling likely to be available in the future (e.g., production of chemicals in bio-refineries).

The main treatment options for biodegradable waste are described in Table 4.2. Anaerobic digestion for bio-waste separated by source and MBT for mixed bio-waste are the key options related to biogas production from biodegradable waste.

Bio-waste management often produces recycling products (e.g., compost and digestate) and energy. This generally results in positive environmental effects. Digestate (from AD) can be either: directly used as fertiliser applied beneficially to fields, or composted to produce compost for beneficial use in horticulture or farming.

Landfilling is the most common MSW disposal method in the EU and elsewhere. Alternatively, bio-waste can be digested, composted, gasified, or incinerated. As the efficiency of incineration is lower for moist bio-waste, it can be beneficial to remove moist bio-waste from residue streams before treatment. Composting, the most common biological treatment, is well suited for green waste and woody material.

Table 4.2. Treatment options for bio-waste (JRC 2011)

Option	**Description**
Source-separated bio-waste collection	
Anaerobic digestion	Solid and liquid digestion with and without post-composting of digestate, high and low efficiency of the energy recovery system, dry or wet, mesophilic or thermophilic, continuous or discontinuous, 1-stage or multi-stage. Gains linked to energy production and use as fertiliser in agriculture.
Composting	Open and closed types (pile, tunnel, composting in boxes/containers, etc.), centralised or home composting, type of ventilation system, maturation time. Gains linked to use as fertiliser in agriculture.
Pyrolysis and gasification	Mainly applied to dry streams, with the intention of burning for energy recovery. They are intrinsically attractive technologies but still present technical challenges and cannot be considered as technically mature enough for bio-waste management. Could also be applied to mixed streams.
Mixed waste collection (i.e. bio-waste together with non-organic fractions)	
Mechanical biological treatment	Pre-treatment to separate biodegradable waste, followed by treatment similar to “source separated waste.” Separation is based on mechanical properties. Possible treatments of organic fractions are composting (stabilization), and anaerobic digestion with energy recovery. In case of AD, additional treatment of the digestate (composting) is needed before use as filling/covering material or before incineration.
Incineration	Type of flue gas treatment. Efficient energy recovery (energy recovery is currently widespread and even systematic in new plants).
Landfilling	Recovered landfill gas can either be burned in flares or recovered for energy (electricity and/or heat).

Mechanical-biological treatment (MBT) combines biological conversion with mechanical treatment (sorting). Mixed waste pretreatment is oriented to the production of either a more stable input to landfill or to generate a product with improved combustion properties. MBT involves anaerobic digestion which technically makes it a process for energy recovery. Combustible waste sorted out in MBT processes may be further incinerated.

4.2.3 Supply chain technology and system integration

4.2.3.1 Examples of highly efficient and competitive logistical systems

One of the most distinctive characteristics of AD is its ability to generate energy from high-volume, low-value, and low-energy-density feedstocks using simple, safe, and relatively cheap production units. AD generates a co-product which is suitable for recycling of plant nutrients and organic matter to the soil.

As AD requires very little input other than biomass, is self-sufficient in energy, it is an efficient source of bioenergy. It can potentially convert large amounts of residues in an economical and sustainable way, and is almost unsurpassed in terms of efficiency in reducing GHG emissions.

Effective AD installations for MSW digestion have been developed at many scales. Implementation, however, still remains below its potential. Separate MSW collection schemes function successfully in many countries, especially for green waste. Kitchen waste is more often collected and treated as part of mixed MSW. The benefits of separate collection can include diverting easily biodegradable waste from landfills, enhancing the calorific value of the remaining MSW, and generating a cleaner bio-waste fraction that allows the production of high-quality compost and facilitates biogas production.

4.2.3.2 Technical and logistic challenges to realizing mobilization potential

There are several reasons which explain the current state of AD implementation, which is significantly below its full potential. Main barriers for AD implementation are found in the fact that AD technology has not yet been proven for all feedstocks.

Generally, markets necessary to support large-scale economic and efficient AD development tend to be immature or may be lacking altogether. This is often the case for residue and effluent conversion in the food and animal feed industry (applicable to most of the fruit, beverage, and animal feed sectors). When feedstock logistics are not effectively organized, owners of AD installations (often farmers) are confronted with major problems in planning and managing the digesters. Price, composition, and quality of substrates may be less than anticipated and tend to show huge variation, seriously hampering the technical, economic, and environmental performance of digesters.

Doubts have risen about the economic competitiveness of AD installations. Especially when co-substrate price, quality, and availability are not as required, profitability of AD operations may be below what is economically feasible. This adds to problems that households, farmers or even companies are facing in obtaining sufficient investment credit for the development of new AD capacity.

Added to this is the fact that the prospects for the sale and delivery of biogas, upgraded “green” biomethane and generated electricity, are generally bleak. In many cases, (potential) AD operators and investors are confronted with huge problems in securing contracts to deliver their products to the grid. This is especially the case for potential use of excess heat, which cannot be transported economically over distances longer than a few hundred meters and for which no local market exists in most cases.

4.2.3.3 Opportunities to increase logistical efficiencies and reduce feedstock delivery costs

Logistical barriers for biogas chains based are mostly related to issues of MSW collection and transportation. MSW collection and treatment in **Europe** has become more complex due to the introduction of pre-treatment facilities. EU member states and many other countries following the requirements set out in EU legislation adopted strategies to shift their waste management up the waste hierarchy. In practice, countries are often inclined to choose options such as incineration or land-filling.

Efficiency of waste collection and digestion can be improved at higher collection rates while a larger number of treatment facilities will help to reduce transportation costs.

4.3 OIL PALM RESIDUES

4.3.1 Factors affecting supply

The potential of bioenergy in Indonesia is estimated at some 50,000 MW, of which just 3.5% (1750 MW) had been realized in 2010. The installed capacity from palm oil residues in 2012 was 61 MW, with an expected increase to 378 MW in 2015. Oil palm is the main source of plant oils in the world, and an important factor for rural area development in equatorial regions of South East Asia, Africa and South America. Covering an area of over ten million ha in the Far East, almost half in Indonesia, oil palm is one of the most important sources of crop residues in the region, providing a large potential feedstock for biogas production.

The global demand for palm oil is projected to increase from the current level of 51 million tonnes to 75 million tonnes by 2050 (Henriksson 2012). This matches the predicted demand that can be met by crop-area expansion and yield increase. Ensuring national food security will probably be the main driving force for increased palm oil production in Africa and South America, and Malaysia and Indonesia will remain the main exporters of palm oil.

In 2013, the total area devoted to oil palm plantations in Indonesia was estimated at 10.8 million ha (Henriksson 2012, USDA Foreign Agriculture Service http://www.pecad.fas.usda.gov/highlights/2013/06/indonesia/). Approximately 85% of global palm oil production is based in Malaysia and Indonesia. Malaysia has only 0.6 million ha available for additional oil palm plantations, and Indonesia up to 24.5 million ha. However, the link between oil palm expansion and illegal logging, deforestation, and diminishing biodiversity has prompted the Indonesian government to restrict expansion of oil palm plantations and instead encourage the use of idle, degraded, and marginal land.

Palm oil yield is currently 3.5 tonnes per ha, about half of the potential. A yield of 6 tonnes ha^{-1} would allow existing oil palm areas in Indonesia and Malaysia to cover the forecasted demand for palm oil until 2050. The biogas potential from oil palm residues will not increase proportionally, but yield improvement and targets for use of palm oil in domestic energy production will be determine the amount of crop residues and palm oil mill effluent (POME) in these regions in the coming decades.

4.3.2 Overview of palm oil residue opportunity

The production of one tonne of crude palm oil requires 5 tonnes of fresh fruit bunches (FFB). Some 3.8 tonnes of stems and 14 tonnes of fronds are generated per tonne of FFB; most remain on the plantation in order to recycle nutrients, improve soil quality, and prevent soil erosion (Schmidt 2007). Processing of one tonne of FFB generates 0.23 tonnes of empty fruit bunches (EFB) and 0.65 tonnes of palm oil mill effluent (POME) suitable for biogas production (Yoshizaki et al. 2013, Wulfert et al. 2002, Lam and Lee 2011).

Additionally, 0.14 tonnes of fiber and 0.05 tonnes of nut shells are generated. These are mainly used on site to cover the heat and electricity demand of oil mills (Stichnothe and Schuchardt 2011). More than 650 oil mills operating in Indonesia have an installed processing capacity of approximately 35 tonne of FFB per hour. The annual potential of residues from palm oil mills (POMs) is shown in Figure 4.1.

Most treat POME in a series of open ponds. The first pond is anaerobic; the second anaerobic or aerobic. The ponds have no bottom liner, so there is leakage to groundwater while methane is emitted to the atmosphere. Yacob reports methane emissions of 1,043 kg per pond per day (Yacob et al. 2005). Less than 5% of the mills in Indonesia apply methane capture. The biogas of capture ponds is frequently flared but rarely used.

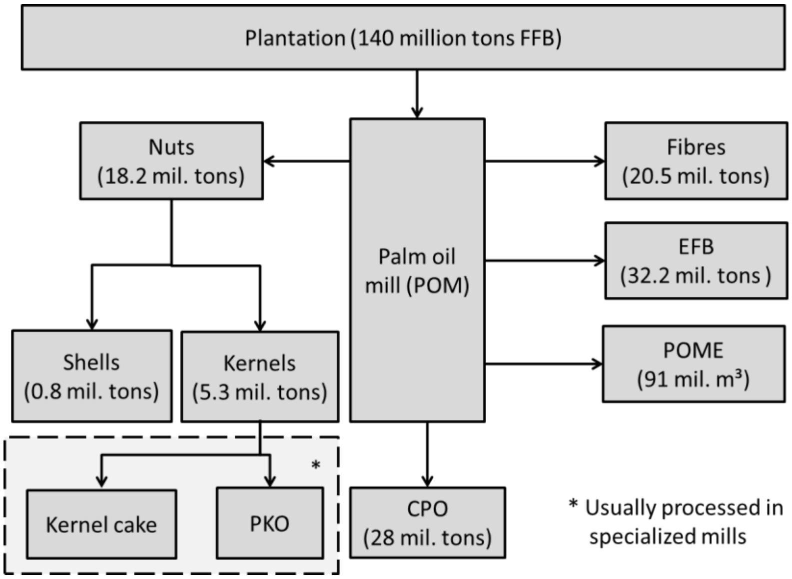

Figure 4.1. Annual potential of residues from palm oil production in Indonesia based on production data from 2012.

Following calculations presented above, Indonesia could generate 32 million tonnes of EFB plus 91 million m^3 of POME. Together, these can provide a maximum of 1.8 billion Nm^3 of biogas (66 TJ). Assuming this is half of global production, total potential for biogas production from oil palm residues would amount to 0.13 EJ. The global assessment provided by E4Tech (2013), 0.3 EJ, seems too optimistic.

4.3.3 Economic and environmental competitiveness of oil palm residue biogas relative to reference energy production systems

Biomass availability or “feedstock” costs for residues is not expected to be a barrier for development of biogas potential. Oil palm residues can be obtained by plant owners or managers at no cost, as they are generated during processing of full fruit bunches and therefore linked to the oil production process[1]. Some residue and waste streams (such as palm oil mill effluent or POME) may have a negative value, as existing or alternative processing approaches can bring significant costs.

Empty fruit bunches (EFB) in Indonesia are usually returned to the field as mulch, or sometimes disposed on the plantation area. There are no official dumping sites; if EFB are disposed then it is in 5-10 km distance from the oil mill. Transportation costs are estimated at 0.1 €/tonne/km.

Treatment costs for effluent (POME) are difficult to assess as they depend on a number of factors. POME often is considered as a profitable but mostly un-tapped feedstock for biogas production. Data from Chin et al. (2013) suggest a 60 tonne FFB/hour palm oil mill in Malaysia produces 234,000 m^3 of POME per year, containing 2,400 tonnes of methane. This could generate 13 million kWh of electricity which would—assuming a feed-in tariff of US $0.08/kWh —represent over US $1 million of electricity sales per year. Net profit would be US $4/$m^3$ of POME.

Generally, cost benefit analysis for POME treatment systems utilizing biogas for electricity production suggests investments in AD installations can be recovered within a period of five year (Schuchardt et al. 2008, Chin et al. 2013, Jala et al. 2014).

Biogas production from oil palm residues is associated with a very favourable GHG budget. Closed tank digestion prevents spontaneous methane emissions from empty fruit bunch decomposition as well as commonly applied open POME ponds. One cubic meter of POME can cause up to 12 m^3 methane emissions, equal to approximately 200 kg CO_2eq. As worst case EFB is dumped and one tonne could cause GHG-emissions equivalent to 1,000 kg CO_2eq. Consequently, using residues of palm oil mills for biogas production is economic, environmental beneficial and saves fossil resources.

4.3.4 Supply chain technology and system integration

As was discussed above, empty fruit bunches (EFBs) are mostly returned to the plantation as mulch. Sometimes, however, they are dumped. Problems faced in EFB mulching are long degradation time, harbouring of snakes, and high costs associated with transportation and distribution (Sunitha and Varghese 1999, 2009). EFBs are not commonly used as boiler fuel due to their high moisture content and moderate calorific value (4–5 MJ/kg) (Hansen et al. 2012, Budiharjo 2010). EFBs have the potential to be used in biogas plants but are not the preferred feedstock because of their high lignin content and associated problems.

Micro-organisms that degrade palm oil mill effluent (POME) can be used to enhance biogas yields in anaerobic digesters. Actual yield levels depend mainly on chemical-oxygen-demand concentration and residence time in the reactor. In North Sumatra, just three palm oil mills apply methane capture, only one of which is utilizing POME for biogas production. The treated POME frequently has a organic load

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[1] In the future, the value of EFB might be based on its nutrient content.

(COD) value between 1,000 and 8,000 mg per liter, well above the allowed values. Therefore treated POME is also applied to the land, although irrigating palm oil plantations is usually not required from a crop water-balance regulation perspective.

4.3.5 Logistical analysis of current systems

4.3.5.1 Examples of highly efficient and competitive logistical systems

Oil palm residues are produced throughout the year and thus can be considered as a major source for power production, particularly in rural areas. Examples of residue digestion are limited. It is estimated that 85% of palm oil mills in Malaysia use open ponds; the remainder utilize open digestion tanks (Jala et al. 2014). Estimations for other regions are scarce.

4.3.5.2 Opportunities to increase logistical efficiencies and reduce feedstock delivery costs

Logistics are not an issue as the residues are generated at the oil mill and almost all oil mills produce sufficient residues to run a biogas plant. Therefore, biogas plants should be built close to the mills to allow the existing infrastructure to be used to transport the residues to the biogas plant. It is expected this applies to Indonesian supply chains as well as other regions of the world.

4.4. CO-DIGESTION

4.4.1 Factors affecting supply

Early farm digestion installations in **Europe** were fed with pure animal manure. Recently, energy crops, agricultural or industrial by-products, and/or grass have been added. The main substrate used is a mixture of energy crops, e.g. maize silage, and animal manure (Persson and Baxter 2014). Installations in Germany generally run on mixtures of manure and maize (Pöschl et al. 2010). Most large-scale fermenters are stirred, solid materials making up no more than 15% of the feedstock, but some large reactors run on dry solid substrates (dry anaerobic composting).

In **Europe**, agricultural co-digestion has become a standard technology. Many small and medium-sized farm scale digesters use high amounts of single or mixed co-substrates together with manure. In 2002, about 2,000 agricultural plants were in operation in Germany, most of them using co-substrates. Considerably fewer were functioning in Austria (110), Switzerland (71), Italy (>100), Denmark (>30), Portugal (>25), Sweden, France, Spain, England, and some other countries (Braun and Wellinger 2003).

It is common practice for crops to be co-digested with manure or other liquid substrates to promote homogenous or stable conditions within the digesters. This allows a process similar to wet digestion, whereby the dry solid content in the digester is below 10%, which enables effective reactor mixing. In most cases mechanical stirrers are used to mix the digester contents (Murphy et al. 2011).

Energy crops such as maize, sunflower, grass, and beets are added to agricultural digesters, either as co-substrates or as the main or in some cases as a single substrate (Braun and Wellinger 2003). A survey by Nova Institute (Carus 2012) shows that some 15 million tonnes of agricultural biomass in EU27 was used for bioenergy in 2007. Major crops involved are maize (6.0 million tonnes), and sugar beet (5.2 million tonnes).

There is a growing trend to blend feedstock for biogas systems in the **USA**; a growing number of existing and planned projects combine multiple feedstocks within a given installation. As the biogas industry deploys more digester facilities across the country, shortening transportation distances will enhance the potential for blending feedstocks (USDA, EPA and DOE 2014).

4.4.2 Economic and environmental competitiveness of co-digestion biogas relative to reference energy production systems

Data on economic performance of AD installations running on manure and co-substrates are difficult to obtain. Economic perspectives in the Netherlands are bleak (Gebrezgabher et al. 2010), but may vary with scale, subsidy level and marketing of excess heat (De Mey 2013). Perspectives in the Belgium, Estonia, Poland and the UK apparently are better, be it that here also large differences in profitability occur (Yeatman 2007, Monson et al. 2007, De Mey 2013).

Farmers in countries like Germany, Austria (Walla and Schneeberger 2005) and Italy (Torquatti et al. 2014) have been able to profit from high feed-in tariffs. An economic analysis of co-digestion of diverse co-substrates in the USA suggested investment and operation costs are high and cannot be recovered (ECO 2009, Moriarty 2013).

When evaluating economic competitiveness of co-digestion, a distinction must be made between costs of manure on the one hand and a range of potential co-substrates on the other hand. Manure is expected to remain available at low cost in considerable quantities, especially in areas with large numbers of livestock (western Europe, the United States, parts of Latin America). In these regions, transportation costs may be the most significant part of manure feedstock costs.

Due to high water content, manure is not likely to be transported over long distances (>20 km) purely for energy (biogas) purposes. Costs for co-substrates vary widely and can weigh heavy on the profitability of the installation as do high investment costs (e.g., Gebrezgabher et al. 2010, Torquatti et al. 2014).

It seems too early to draw generic conclusions on profitability of co-digestion, which mostly depends on local conditions, installation costs, co-substrate availability and subsidy levels (Gebrezgabher et al. 2010, De Mey 2013, Torquatti et al. 2014). Whilst many co-substrate have shown promising yields in laboratory studies, improvements are needed in models that can simulate yields in practice. More research is needed on the exploitation of co-digestion installations (Atandi and Rahman 2012).

Digestion of animal manure is an effective way to prevent spontaneous methane emissions normally associated with manure storage and application. It is estimated that 18 million tonnes of methane may be released from untreated manure per year (FAO 2006), which is equivalent to almost 500 million tonnes of $CO_{2\text{-eq}}$ per year. Apart from the prevention, manure has a huge biogas potential. It remains unclear how much of this potential can be realized.

AD chains running on pure manure will have the most favorable impact, as cultivation of co-substrates (usually maize) lead to increased GHG emissions. Notwithstanding this, co-digestion is considered an effective way to combat climate change (Han et al. 2011, JRC 2014, Styles et al. 2015). As profitability of biogas installations increases with scale, small scale biogas plants treating only manure—which might be preferred from an environmental point of view—will probably be less profitable than larger co-digestion installations.

4.4.3 Supply chain technology and system integration

In the past, anaerobic digestion (AD) was mostly a single-substrate, single-purpose technology. Currently the limits and the potential of AD are better known, and co-digestion has become a standard technology in agricultural biogas production (Braun and Wellinger 2003, Pöschl et al. 2010, Murphy et al. 2011). Four types of anaerobic digesters can be used to treat livestock waste (Mathias 2014):

- Continuously stirred tank reactors (CSTR)
- Upflow anaerobic sludge blanket (UASB) reactors
- Upflow anaerobic filter (UAF) digesters
- Baffled digesters.

Co-digestion generally involves wet single-step processes such as CSTRs. The substrate is normally diluted with around 8–15% dry solid content. Wet systems are particularly useful when the digestate can be directly applied on fields and green lands without separation of solids (Braun and Wellinger 2003). Anaerobic digestion of crops often requires prolonged hydraulic residence times (several weeks to months), involving both mesophilic or thermophilic temperatures. Complete biomass degradation, leading to high gas outputs, is essential for a healthy economic performance and minimized GHG emissions. Volatile solid degradation efficiency should be 80 to 90% (Murphy et al. 2011).

Most agricultural installations in Germany run on a mixture of manure and maize (Pöschl et al. 2010). In 2013, about 8,000 agricultural plants were in operation in Germany, most of them using co-substrates. Considerably fewer were functioning in Austria (293), Switzerland (96), France (105), the Netherlands (105), Denmark (67), and the UK (63) (Persson and Baxter 2015).

Many modern reactors consist of three closed reactor tanks. The first reactor converts easily degradable materials (cellulose, sugars, amino acids, fats, and glycerol) into biogas, a process accompanied by the build-up of volatile fatty acids and lactate. Resistant lignocellulosic components are digested in the second reactor, the third reactor serving mostly as a digestate storage tank. During this stage, production of biogas continues, albeit at a low rate (Zwart and Langeveld 2010).

It is common practice for crops to be co-digested with manure or other liquid substrates to promote homogenous or stable conditions within the digesters. This allows a process similar to wet digestion, where the content of dry solids in the digester is below 10%, which enables effective reactor mixing. In most cases, mechanical stirrers are used to mix the digester contents (Murphy et al. 2011).

The most common digester model in southern **Brazil** is the so-called Canadian digester, which has a volume of some 150 m^3 and a gas holder capacity of 136 m^3. The hydraulic retention time is 30 days. It can treat manure of a 50 sow pig farm. The generated biogas is used for heating poultry farms, domestic applications, or grain driers (Mathias 2014).

4.5 ECONOMIC COMPETITIVENESS OF BIOGAS PRODUCTION SYSTEMS RELATIVE TO REFERENCE ENERGY PRODUCTION SYSTEMS

Biogas is one of the cheapest bioenergy sources, with production costs generally remaining below US $4/GJ (IRENA 2014); however, poor economic performance of digesters can be an important barrier for the mobilization of biogas potential. Specific performance of biogas production chains depends on local economic conditions, dominated by feedstock availability and associated costs for its production, collection, transport, and pre-treatment.

Biomass cost supply curves may be rather steep, showing a strong rise in feedstock prices needed to stimulate availability of larger volumes of sources. This is, however, not always the case. Biogas feedstocks are often either negatively priced or available at very low prices with slow increases in feedstock costs. Some feedstocks in Ireland, for example, are only available at prices exceeding 200 Euro per tonne (US $6.0/GJ, assuming an exchange rate of US $=0.80 Euro; Clancy et al. 2012). These prices are unlikely to be covered by biogas production chains.

Global cost supply curves for biogas feedstocks are presented in Figure 4.2. Availability of biogas resources is projected to amount to 35 EJ at production costs lower than US $2/GJ. Future availability could exceed 90 EJ at less than US $3/GJ. The figure suggests that feedstock prices will be slightly higher in 2050 as compared to the current situation.

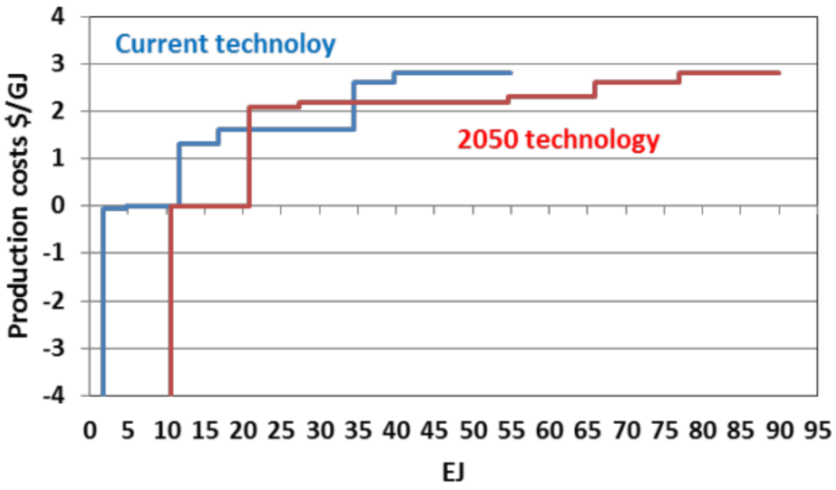

Figure 4.2. Cost supply curve of MSW, animal waste, and crop residues. Source: Rogner et al. 2012.

investment and depreciation. Operational costs make up the difference. Cost shares will, however, vary among regions and feedstock types. Highest feedstock costs are expected for co-digestion of energy crops which are cultivated specifically for this purpose. Lowest costs may be found in MSW and specific other waste streams, which can have negative prices as indicated above.

Even when feedstock costs are low, collection, storage, and preparation of the biomass will be costly. This is especially the case for wet materials that must be transported over long distances (manure being the most unfavourable example).

The production and use of biogas can be an effective way to reduce GHG emissions (Han et al. 2011, Agostini et al. 2015) and has significant potential in Europe (E4Tech 2013) and the United States (USDA, EPA and DOE, 2014). Applied in transportation, biogas supply chains are more GHG-efficient than their fossil alternatives. They may reduce emissions up to 80% from natural gas (IEA 2011, JRC 2014). The actual reduction level depends on a number of factors including the feedstock that is used, efficiency of the biogas conversion, and the way the production chain is organized.

Minimum GHG saving for biofuels, as mandated in USA and EU policies, ensures that biogas contributes to emission reduction targets. The highest reduction levels can be realized in situations where large amounts of waste and residue are available and transport requirements are limited. In practice, emissions related to the cultivation of energy crops used as substrate or collection of waste or residues sometimes can limit GHG efficiency (Langeveld et al. 2012, Agostini et al. 2015).

Biogas production chains have a unique characteristics. Not only can they generate energy with low GHG impacts; they also can prevent spontaneous GHG (methane, nitrous oxide) emissions occurring during the decomposition materials that would otherwise (largely) remain unused. Hence, application of MSW, waste and residue flows may realize extremely low or even negative GHG impacts (e.g. JRC 2014, Agostini et al. 2015, Styles et al. 2015a).

When applied in electricity and heat production, biogas from waste and residues is causing less GHG emissions than any fossil alternative – including natural gas (Han et al. 2011, IEA 2012, JRC 2014). Important advances of biogas production are related to the fact that digestate can serve as source of nutrients or soil organic matter, hence reducing the need for artificial fertilizers and enhancing soil quality (Braun and Wellinger 2003). AD requires little energy and has a very favourable energy output-to-input ratio.

Biogas production offers interesting options to increase efficiency of land use (e.g. Berndes et al. 2011, IEA 2011). Indirect effects from biogas production are scarce and are mainly limited to the production of dedicated energy crops in co-digestion chains. In some cases, waste streams originally dedicated to animal feed may be involved (Langeveld et al. 2012, Styles et al. 2015b). Methane leakage during or after the digestion process is an important risk to mitigate for reducing the potential GHG impact of biogas chains (Han et al. 2011, JRC 2014, Agostini et al. 2015).

Negative prices of MSW have been suggested, as gate fees for composting sites (the main alternative disposal route) are implemented in some countries. Consequently, AD managers receive a compensation for treating MSW expressed as a bonus per tonne treated. This helps to compensate costs made for digestion of MSW. Gate fees in Ireland are around 80 €/tonne. It is expected that a bonus of 70 €/tonne will AD installations to attract 50% of available MSW in this country. A further 25% may be sourced if the bonus is reduced to 40 €/tonne; the remaining 25% to become available at at 0 €/tonne (Clancy et al. 2012).

Experiences in the UK show that gate fees for AD vary between 41 to 71 €/tonne of MSW, with a median of 48 €/tonne (Clancy et al. 2012), although higher fees have been reported (up to 96 €/tonne, Monson et al. 2007). In Belgiam, a gate fee of 40 €/tonne was used for separately collected garden-fruit-vegetable waste. This value was used as a general proxy in a techno-economic assessment study for digestion of bio-waste combined with composting of the digestate (Devriendt et al. 2013).

Gate fees for bio-waste are common throughout Europe. An overview of gate fees and landfill taxes (FhG-IBP 2014) shows fees can be very low in Eastern European countries while Luxembourg and Germany fees are around 140 €/tonne. Landfill taxes range between zero and 100 €/tonne, but the total cost never exceeds 150 €/tonne and is subject to change. Gate fees in Ireland apparently are dropping due to overcapacity as food waste production has recently declined (Clancy et al., 2012).

Food waste gate fees in the south of the US have been reported at US $30/tonne, or approximately 25 €/tonne (Moriarty 2013).

Biogas can reduce GHG emissions most significantly if used as a biofuel for transportation or directly injected into the gas distribution grid. Its use as biofuel could result in significant reductions of GHG emissions, showing a net advantage with respect to other transportation fuels. The residues from the process, the digestate, can be composted and used for purposes similar to compost, thus improving overall resource recovery from waste.

Biogas production from MSW is a very favorable option to reduce GHG emissions. Application of biogas in electricity production provides emission performance levels better than any fossil alternative. Reduction rate of spontaneous methane emissions are listed as 40% to 50% for covered landfills (e.g., Baldasano and Soriano 2000) more than 90% of emissions from open dumps (Manfredi et al. 2009). The impact of reduced methane emissions can be huge, especially in developing countries where MSW contains relatively high amounts of fermentable biomass.

4.6 SUSTAINABILITY

4.6.1 Sustainability performance

Anaerobic Digestion (AD) offers significant advantages for realization of the bio-energy potential contained in organic materials as a result of its economic, technical and environmental sustainability performance as reported in numerous studies (Pabón 2009, Yu et al. 2010, Gregory 2010, Murphy et al. 2011, Deublein and Steinhauser 2011, Rajendran et al. 2012, Hamlin 2012, Da Costa Gomez 2013, FAO 2014, Quist-Wessel and Langeveld 2014, JRC 2014, Styles et al. 2015a).

Technically, AD is a well-established technology, especially in developing countries. Household-level installations are mostly found in Asia, but it is also being applied at an industrial scale. AD is a flexible technology that can process dry and wet feedstocks including manure and waste streams such as municipal sludge (see also section 4.2).

Only few research papers address performance of biogas supply chains as an independent biofuel. It is typically dealt with as a sustainable option for waste treatment in biofuel production chains, complex waste management installations, food processing, or other industrial processes involving organic materials. If integrated into larger systems, it can significantly improve energy efficiency, upgrade waste flows, and reduce GHG impacts. Treating manure and other MSW in a digester reduces its content of contagious organisms and the risk of environmental microbial contamination (e.g., Rajendran et al. 2012), although not all risks are fully eliminated. This sanitation effect is especially relevant for rural household applications in Asia (Cheng et al. 2014), Africa (AfricaBiogas 2015) and Latin America.

Han et al. (2011), Agostini et al. (2015) and Styles et al. (2015a, 2015b) addressed independent biogas supply chains, and showed that AD has a very favourable energy output-to-input ratio and a high potential to reduce GHG emissions. For example, cultivation and processing of palm oil is potentially a large source of GHG emissions, and biogas production may reduce net supply chain GHG impacts. Its positive performance is enhanced by the prevention of spontaneous GHG emissions from untreated feedstocks (MSW, manure, waste and residues). When such benefits are included, biogas supply chains may have extremely low, or even negative, GHG balances.

AD also helps to reduce air pollution from particulate matter, soot, and nitrogenous gases (Arshadi and Sellstedt 2008, Gregory 2010, Quist-Wessel and Langeveld 2014) and improve wastewater quality (Cheng et al. 2014, Persson and Baxter 2014). AD residues are stable and rich in nutrients and organic matter, and may be recycles on farms to enhance nutrient recycling and improve soil quality (Yu et al. 2010, Gregory 2010, Rajendran et al. 2012, Da Costa Gomez 2013).

Biogas may also provied economic and social benefits. Digesters are generally safe, compact systems that are relatively easy to operate, and the produced methane is a clean alternative fuel at industrial as well as household levels. In developing countries, AD can save time for cooking and reduce lung damage compared to the collection and burning of firewood and charcoal. As household and farm installations can be constructed with local materials that are widely available, they can contribute to increased welfare and be a cost-effective upgrade of human waste and other crop and animal waste streams for poor households. In palm oil production, it may create income at the lowest level in the supply and value chain; and decentralized renewable energy stimulates economic development, especially in land-locked nations or isolated inland regions. Economic performance depends on biogas yield, installation costs, and feedstock fees (Gebrezgabher et al. 2010, Cheng et al. 2014).

In some cases, production of biogas may have risk of explosion (Arnott 1985) and toxicity from the hydrogen sulphide fraction; workers entering digesters without using oxygen masks have been killed. Challenges also include odors and leakages due to relatively short lifespan of construction materials (Rajendran et al. 2012).

4.6.2 Sustainability governance

Sustainability criteria specifically for biogas are not common, but simple requirements have recently been adopted by Danish legislation (BEK nr. 301 2015, DEA 2014). The legislation stipulates that biogas production should mainly be based on residues and waste, and that the input of dedicated energy crops should at maximum be 25% for the period 2015-2017, decreasing to 12% in 2018-2021, with even lower shares expected after 2021. Feedstocks supplies must be reported to the authorities in documentation from 1 September 2015.

Apart from this, biogas also plays a role in programs to combat climate change, especially in OECD member states. For example, the EU Fuels Quality Directive (FQD) and in the Renewable Energy Directive (RED) include typical and default values for GHG impact of biogas supply chains. Modern farm-scale or industrial installations in developed or emerging countries are furthermore often subject to legislation addressing sustainability of the management of waste and manure (see section E). Voluntary governance initiatives, such as the Global Bioenergy Partnership (GBEP) or such certification schemes as the Round Table on Sustainable Palm Oil (RSPO 2012) address biogas as part of a sustainability strategy to treat waste from biofuel production chains.

Generic sustainability indicator frameworks for a broader evaluation of biogas chain performance are being developed, also for use in public or private governance (e.g. Dale et al. 2013), but so far they have not been applied to biogas. An exception is Langeveld et al. (2012) who used an integrated assessment tool to evaluate economic, environmental and social dimensions of three scenarios that use crop or industrial residues for biogas production in the Netherlands.

4.7 POLICY DRIVERS AND BARRIERS

Bioenergy policies generally do not stimulate biogas production, and biogas producers are often caught between policies oriented towards efficient treatment of waste (be it MSW, industrial waste, or manure) on the one side and unfavorable financial profits on the other side. This leads to slow expansion of biogas production capacity, e.g. in the United States, Brazil and many other emerging and industrial countries), as well as negative economic perceptions where capacity is developed (e.g. in the Netherlands).

Exceptions to this rule are mostly found in China, India and Africa, where development of household installations is mostly driven by the need to improve energy independence at the household level, and in some European countries (e.g. Germany, Austria, and Italy), where specific supporting policies are dedicated to farm-level biogas production. Lessons learned in these countries will be useful for future dedicated biogas policies and research.

Policy drivers and barriers are described below for each of the three biogas supply chains evaluated, In general, important ways to overcome barriers to AD development include carbon pricing to take account of externality costs of alternative fossil fuels; renewable portfolio standards requiring a certain amount of power to be generated from renewable sources; tax credits or subsidies for renewable energy; and feed-in tariffs requiring that utilities purchase energy from certain generation facilities at a favorable rate (C2ES 2015).

4.7.1 MSW

EU member states adopted strategies to move waste management up in the waste hierarchy, and EU and national targets related to such policies are overall drivers of better waste management, including use in biogas production. Energy policies are less important drivers. Generally, the share of EU member states that dispose more than 75% of municipal waste in landfills has decreased sharply, with a subsequent increase in recycling (EEA 2013). However, national bio-waste recycling rates did not improve much, and most countries still prefer to dispose their MSW in landfills. Five countries have already achieved the waste recycling target of 50% recycling by 2020 and another six are well on their way, but most countries will need to make an extraordinary effort in order to achieve the target.

National and regional instruments to fulfil WFD targets are crucial for achieving positive results. They include landfill bans on biodegradable waste or non pre-treated municipal waste, mandatory separate collection of biodegradable municipal waste fractions, economic instruments such as landfill and incineration taxes, and waste collection fees that provide incentives for recycling. Countries using a broad range of policy instruments generally have a higher rate of municipal waste recycling than countries using few or no instruments, and there is some evidence that a correlation exist between the level of landfill taxes and the share of municipal waste that is recycled. Gate fees and regulatory restrictions also play an important role in shaping waste management decisions,

The role of biogas as an energy source is nevertheless expected to remain limited to around 2% in the EU (Beurskens and Hekkenberg 2010). The barriers to effective deployment are mostly policy-oriented (Table 4.3), and includes substantial variation between local and regional policies, that have a significant influence on municipal waste recycling rate (FNR 2015). Even if WFD places landfills lowest in the waste handling hierarchy, higher priority is given to material re-use and recycling compared to digestion. This makes sense from an energy-efficiency perspective, but in practice limits the prospects for AD. At the same time, feedstocks markets are frail, with uncertain price developments and end-user competition for feedstocks.

Table 4.3. EU Policies that regulate management of the biodegradable fraction of MSW.

Instrument	Objective	Remarks
Waste Framework Directive (WFD)	Protect environment and human health, ensure sustainable use of natural resources.	Defines the “waste hierarchy:” (a) prevention, (b) re-use, (c) recycling, (d) other recovery and (e) disposal of waste. Encourages separate collection and recycling of bio-waste.
Landfill	Limit landfilling of	Member states which previously relied

Directive	biodegradable municipal waste reduced to 35% of 1995 levels by 2016.	on landfills are given a four-year extension period (i.e., until 2020).
Directive on Renewable Energy Sources	Use of bio-waste to replace fossil fuels.	Supports use of all sustainable types of biomass for energy, requires development of national action plans to support development of renewable energy, including biomass-based energy.

4.7.2 Oil palm residues

Policies to promote renewable energy, increase energy efficiency, stabilize feedstock supplies, may be drivers for biogas production from oil palm residues (Table 4.4). However, policies addressing GHG emission reductions and improved waste handling may be a more important drivers, as impacts from large GHG emissions and wastewater generation in cultivation and processing can be reduced by biogas production from co-digestion. Policies to promote small-scale electricity production may also play a role, as biogas production can easily be produced in small-scale plants.

Other barriers include a low demands for heat and therefore a limited the desire to use mill effluent and empty fruit bunches as an energy source, low awareness of biogas opportunities and a negative and uninformed image of bioenergy (Dimple 2010). There is a lack of local capability and resources for project design, construction, operation, and maintenance. Assessments of feedstock potentials are needed, as are designs that take account of the isolated location of oil palm plantations, which require large investments in grid access.

Table 4.4. Policies affecting oil palm residue management in Indonesia.

Instrument	Objective	Remarks
Presidential Regulation No. 5/2006	Provide basis for renewable energy development in Indonesia	Elaborated in the Blue Print—National Energy Management 2005 to 2025. Biofuel Decree MEMR Regulation No. 32/2008 sets mandatory utilization framework up to 2025.
Multilateral Clean Technology Fund (CTF)	Accelerate investment in energy efficiency, and renewable energy.	Goal to achieve an electrification rate of 90% by 2020 and reducing GHG emissions 26% by 2020.
Electricity Law No. 30/2009	Secure sustainable energy supply, promote conservation and use of renewable energy.	Intended to increase electricity generation by small- and medium-scale renewable energy plants. Excess power to be purchased by state owned companies, regional companies, and cooperatives.
Ordinance No. 31/2009	Increase share of renewable energy to 25% (2025). Target to increase share of households using cooking gas to 85% in 2015 from 45% in 2013.	Introduce a progressive oil palm export tax to boost national downstream industries, secure domestic supply, and reduce volatility in cooking oil prices (IEA 2013).

Regulation 31/2009	National electricity supplier (PLN) is required to purchase up to 10 MW from independent private producers.	Feed-in tariffs offered vary among different regions in Indonesia.
Regulation No. 25/2013	Reduce fossil fuel imports	No penalty foreseen for sectors that do not meet mandatory targets, but will depend on the difference in market prices between fossil fuels and palm oil.

4.7.3 Co-digestion

Several drivers stimulate development of AD production by co-digestion of several, primarily agricultural waste streams (Braun and Wellinger 2003). One driver includes oversized digesters in wastewater treatment plants, where addition of co-substrates helps to produce more gas and consequently more electricity to cover the plants energy needs at only marginal additional cost. Addition of co-substrates with high methane generation potential to manure alone (which has a relatively low gas yield) not only increases biogas yield but also generates income from tipping fees. Additional drivers include high costs for fossil energy, demand for local energy sources, need for sanitation, and a number of environmental pollution policies.

Policy drivers for biogas production in **Europe** have mainly been (environmental) policies (Table 4.5), especially in Germany, where the introduction of ambitious environmental policies and favorable economic support measures has led to a considerably increase in biogas production (Schütte and Peters 2010). The situation in other European countries is less favorable (see, for example, Persson and Baxter 2014, 2015).

Policies in the **United States** provide modest support for biogas production. Primary laws affecting the development of AD facilities include the federal Clean Water Act of 1972 and Clean Air Act of 1970, and state environmental, agricultural, and public utility regulations, and local building and zoning requirements (Bramley et al. 2011, Table 4.6). For example, the Acts require that large animal feeding facilities must develop Nutrient Management Plans to ensure that manure is applied to the land appropriately. Certain states may also require that smaller farms comply with such Acts to avoid water pollution.

Table 4.5. Policies affecting production of biogas from co-digestion in the United States.

Instrument	Objective	Remarks
U.S. Federal regulations	Set national pollution limits.	Set limits for individual facilities. Operational permits often issued by state or local agencies.
Resource Conservation and Recovery Act (RCRA)	Regulate Waste processing facilities.	Facilities that run on farm manure and apply digestate to farm fields are considered agricultural. When accepting waste from other facilities they may be considered waste treatment facilities.
Clean Water	Regulate concentrated	Issuing National Pollutant Discharge

Act	animal-feeding operations.	Elimination System (NPDES) permits regulating discharges to U.S. waters.

In **Brazil**, the development of agricultural biogas technology has been strongly supported by government policies that consider biogas to be an affordable, self-sustaining, and environmentally friendly form of energy (Table 4.6). Successful biogas development has been boosted by investment programs for bioethanol production, and Brazil has also made effective use of the clean-development mechanism (CDM) to promote agricultural biogas production in its rural areas (Bramley et al. 2011).

Table 4.6. Policies directly or indirectly supporting production of biogas from co-digestion in Brazil.

Instrument	Objective	Remarks
National Policy on Climate Change	Reduce GHG emissions.	Implemented through the adoption of Sectorial Action Plans.
Low-Carbon Agriculture (ABC Plan)	Facilitate implementation of the Sectoral Action Plan in agriculture.	Producers are offered funds from Brazilian Development Bank (BNDES) Rural Savings Booklet and Constitutional Funds.
Brazilian Electricity Regulatory Agency (ANEEL)	Organizes auctions for procurement of renewable energy.	Keeps track of biogas plants connected to the grid; so far only a small number of installations are included.
Legislation for the development of a biomethane market (Draft)	Includes quality standards to be met by biomethane traders.	It was written by the National Agency of Petroleum, Natural Gas and Biofuels.

A dominant barrier for development of biogas production through co-digestion is the often poor economic performance caused by high investment and feedstock costs. An overview of structural barriers suggests lack of knowledge or technical support is less of a problem in the Netherlands than availability of feedstocks, eligibility for tax credits, finding a good location for the plant, and inadequate political and public support (Langeveld et al. 2010). Similar barriers were reported for wastewater co-digestion in Iowa, USA, e.g., restrictive state regulations, lack of funding and access to tax credit, fluctuations in feedstock availability, and cultural and social conditions (Hanson 2014).

Small-scale farm co-digesters may also face limitations, such as options to make use of economies of scale, seasonality of manure collection, access to the grid, lack of financing opportunities, and relatively high fixed costs (Shelford and Gooch 2012). Additionally, the removal of unintended legislative barriers may be very slow. In the Netherlands, it took years before the legal distinction between farm- and industrial-scale digesters was adopted, which made it extremely difficult for farmers to obtain approval to develop larger AD installations on their farms (Langeveld et al. 2010).

In countries with stringent nutrient management legislation to protect water quality, farms operating co-digestion installations may also be required to integrate inputs of additional biomass into existing nutrient management plans. This is the case in parts of the United States and the EU, mainly in dairy and intensive pig farms (e.g., Shelford and Gooch 2012). Other barriers include those reported for oil palm residue-based biogas.

4.8 RECOMMENDATIONS

An overarching recommendation to development of renewable energy alternatives generally is removal of policy supports for fossil fuels. Such support prevents new technologies from becoming competitive and intensifies the competition for scarce public funds. Further policy recommendations essential for biogas mobilization potentials to be achieved include the following.

- Inefficiencies, inconsistencies, and intrinsic barriers for biogas production in existing policies need to be identified and removed at local, regional, and national levels, especially waste and residue treatment policies. In the waste hierarchy of the Waste Framework Directive, there is a need for greater focus on bio-waste recycling.

- Long-term, stable policy support is essential, including sufficient economic incentives for investments in AD installations or infrastructure for marketing and utilizing biogas, upgraded gas, and locally- generated electricity. This may also include favorable feed-in tariffs that are especially needed for biogas production based on energy crops produced on expensive agricultural land.

- Policies should require that relevant sustainability concerns are addressed, including competition with food production when biogas production is based on energy crops.

- The public image of biogas production needs to be improved to remove negative perceptions of biogas production, to ensure support by stakeholders in feedstock production, gas and energy markets, and among the general public.

- The general business case for digester performance needs to be improved. Relatively low energy content per unit of feedstock, high initial investment costs, and considerable logistical complexity and cost are formidable barriers to competitive AD systems. As for the other supply chains evaluated in this project, effort must be placed on developing efficient logistical systems, investment in infrastructure, and RD&D to develop advanced hardware and management systems.

- Develop biogas supply and value chains (including access to the grid of many small biogas producers, biogas storage systems) that are integrated with existing residue management systems (e.g., collection of municipal waste, food waste) to improve the competitiveness of biogas production while also garnering public and political support.

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5

Lignocellulosic Crops Supply Chain

5.1 INTRODUCTION

Agriculture provides food, fiber and bioenergy products but high production can be sustainably achieved only if negative impacts on soils, water, biodiversity and climate are avoided or minimized. Agriculture is also expected to provide other social and economic benefits ranging from rural income and employment to the conservation of cultures and pleasing visual landscapes. Policies to support bioenergy have been promoted in part to address concerns about the negative impacts caused by fossil energy systems, and many risks associated with conventional agricultural production systems and fossil fuels could be mitigated or avoided through the development of sustainable production systems for lignocellulosic bioenergy crops.

Lignocellulosic crops can be cultivated on soils of varying qualities providing high biomass output per unit area. Plants include perennial grasses, such as switchgrass, miscanthus, and others, and tree species, such as willows, eucalyptus, poplars, and others, grown in relatively short rotations both in coppicing systems and/or replanting after each harvest. They represent a promising option for producing biomass for energy and are referred to as one of the most efficient options for reducing greenhouses emissions through fossil fuel displacement. Studies that assess bioenergy potentials for the longer term consistently report that the production of biomass in dedicated plantations is a prerequisite for reaching higher end biomass supply potentials.

During the last two decades, several predictions mostly in Europe, but also in other parts of the world, have indicated the possibility of a dramatic increase in agricultural areas dedicated to lignocellulosic crops in response to European energy and climate targets. Similarly, lignocellulosic crops have repeatedly been identified as an attractive option for bioenergy supply in N. America, Australia, and other parts of the world, with reference to a range of additional environmental services. Emerging options for converting lignocellulosic biomass into refined solid, liquid and gaseous fuels build from access to new feedstock resources and more benign feedstock production systems. It is well-documented that such lignocellulosic cropping systems can be integrated into agricultural landscapes so as to make better use of available resources and provide multiple benefits in addition to the harvested biomass (Berndes et al., 2008; Dale et al., 2011). Not the least, such systems can – through well-chosen site location, design, management and system integration – offer additional ecosystem services that, in turn, create added value (Weih and Dimitriou, 2012). Understanding the positive and negative impacts of different agricultural land management options is critical for the development of management regimes that balance trade-offs between environmental, social and economic objectives that might be partly incompatible.

Yet, many of the lignocellulosic crop options identified as promising future biomass supply sources are either very little used today, or they are used for other purposes such as animal feeding and pulpwood production. Thus, there is a need to get a better understanding of the barriers to large-scale mobilization of these lignocellulosic plant options as bioenergy feedstocks and, based on this, to develop implementation strategies that facilitate sensible establishment and growth of lignocellulosic production systems on agriculture land that are considered attractive from both environmental, social and economic points of view.

This case study concerns lignocellulosic crops that are commercially cultivated for bioenergy or other markets (e.g., pulp and paper production), as well as cropping systems that are presently little used but have much in common with already established options concerning biomass properties and technologies used in the production and supply chains. The scope for the main analysis is limited to feedstock production and supply to a conversion plant. Insights from the other case studies can be used to address the issue of matching feedstock quality with requirements associated with specific conversion systems. A specific focus in this case study is placed on the integration of lignocellulosic crops in the agriculture landscape to provide biomass feedstock while at the same time providing additional benefits, such as enhancing biodiversity, reducing water and wind erosion, improving soil productivity and enhancing soil carbon storage, reducing eutrophication load on aquatic ecosystems and reducing negative environmental effects associated with the cultivation of conventional food and feed crops.

The aim of this chapter is to analyze methods integrating lignocellulosic crops in the agriculture landscape to provide biomass feedstock while at the same time providing additional ecosystem services. This is done by describing and analyzing several examples of lignocellulosic cropping systems in agriculture, studying their context and approach in terms of drivers, presenting in general terms the evaluation of the related sustainability issues in terms of environment, social and economic impact, and analyzing general and case-specific constraints and opportunities of such systems towards a wider implementation.

Initially, some examples of different lignocellulosic systems in Ireland, Australia, USA, Germany and Sweden will be briefly described, focusing on biomass production systems and stating clearly how dedicated ecosystem services can be provided by these systems. After the analyses of all the examples, the constraints that might exist and that need to be taken into account towards a broader implementation will be listed, as well as the opportunities that lignocellulosic systems provide as a biomass feedstock for energy.

5.2 LIGNOCELLULOSIC CROPS IN AGRICULTURAL LANDSCAPES — SYSTEM AND OPERATIONAL ANALYSES

The outcomes of this chapter, in terms of sustainability issues as well as on opportunities and constraints of lignocellulosic crops in agriculture towards a broader implementation, are a result of the experience gained from several examples from different parts of the world where different ecosystems services are provided through these systems. Despite the different features of the systems, due to e.g. case-specificity and differences in the starting point and background in each area or country, the analyzed examples can be considered as representative for implementation in other parts of the world. There are also several similarities in the drivers, opportunities and constrains identified between the different systems, showing that some general conclusions on the way forward towards a broader implementation of lignocellulosic crops could be drawn. For the purpose of this draft, some indicative production systems have been chosen to be presented, selected based on the lignocellulosic crops used, and keeping into account the most dominant ecosystem service provided and the parts of the world they are implemented (from Task 43 countries), in an effort to be as representative as possible. Therefore, we include two examples focusing on “production” (sections i and ii), two focusing on “selecting implementation areas” to achieve the highest positive impact on certain ecosystem services (sections iii and iv), and finally two examples where applied large-scale “multifunctional lignocellulosic crop planting are described (sections v and vi). A more detailed analysis of the background of these examples, as well as the research results behind of these systems are provided in the comprehensive full report (Dimitriou et al. 2015).

5.2.1 Production of short rotation willow for bioenergy in Ireland

In an effort to promote the use of bioenergy in Ireland and to contribute to meeting the EU targets, the government set out to implement co-firing of biomass at three peat-fired electricity generating plants owned by the state. The co-firing targets are limited to co-firing 30% of the maximum rated capacity in any plant until 2017, 40% between 2017 and 2019, and 50% thereafter (Anonymous, 2009). Three hundred kilotonnes of biomass will be required to achieve 30% co-firing at Edenderry power plant alone. In order to meet this demand, additional quantities of biomass to those currently co-fired will need to be obtained. Short rotation coppice willow (Salix sp.) (SRCW) has been cultivated as an energy crop in Ireland to help meet the biomass demand of the three peat-fired power plants. In order to promote the cultivation of willow among farmers, a bioenergy scheme was introduced in 2007 that offers financial support for the establishment of willow crops. Similarly, the operator of Edenderry power plant offers support to farmers willing to establish a willow crop and supply it to the power plant. These incentives have led to an increase in willow planting since their inception, from around 100 ha in 2008 to more than 800 ha of willow crops planted in Ireland in 2015. In 2010, 5,208 tonnes of willow chip were co-fired with peat in Edenderry power plant, representing 5.4% of total biomass co-fired in Ireland on a mass basis. With the co-firing target increasing to 30% by 2017, a substantial increase in the area of energy crop plantations will be required.

To further increase the SRCW land base needed to reach the expressed targets in Ireland, the importance of policy measures including incentives in promoting the uptake of energy crops have been clearly stated in many countries, not only in countries such as Sweden, which is now the European leader in SRCW for energy production on agricultural lands (Mola-Yudego et al. 2014). Despite the incentives needed that will come from political decisions, the features of the crops that will be potentially supported for broader implementation need to be adapted to the specific edaphoclimatic conditions in the area to ensure high production per unit area, and need also to offer other ecosystem services besides the biomass that will fulfil other governmental environmental, social and economic goals. In the case of willow, the crop is known to be suitable for cultivation on medium fertility sites, thus not competing for the most fertile land, which is currently used for food production. Moreover, the long life-span of willow crops (20 plus years) allows the accumulation of soil carbon in mineral soils, as well as promoting stable nutrient cycling and soil biological activity, resulting in increased soil fertility when compared to conventional agricultural crops. In addition, the cultivation of willow promotes higher biodiversity when compared to conventional agricultural crops. Willow crops are also known for their bioremediation potential. Willow has been proven to effectively take up nutrients and heavy metals and can, therefore, be used for treatment and utilization of nutrient-rich municipal residues such as wastewater and/or sewage sludge, improving treatment efficiencies, but also the economic welfare of the farmers (Dimitriou and Aronsson, 2005). Under the Irish context, willow is an appropriate crop since it has relatively high water requirements, and the vast majority of Ireland receives upwards of 800 mm of rainfall per year. Surveys carried out with Irish farmers have shown high willingness of farmers to adopt energy crops in Ireland, with over 70% of respondents indicating interest in producing energy crops (Augustenborg et al. 2012).

All the above indicate that the potential of SRCW in Ireland is high, and therefore studies to evaluate the energy requirements and environmental impacts associated with the cultivation, harvest, and transport of SRCW for energy utilization in Ireland have been conducted to quantify this potential. Detailed life cycle inventory (LCI) data for willow cultivation in Ireland considering a number of scenarios based on different management The LCA is carried out in accordance with the steps outlined in the International Standards on life cycle assessment, namely; goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation (ISO 14040

2006, ISO 14044 2006). The LCA software SimaPro v7.3.2 (PRé Consultants 2011) was used to construct the LCA model and undertake the impact assessment calculations.

The aim of this study is to evaluate the energy requirements and environmental impacts associated with willow (Salix sp.) cultivation, harvest and transport. Different management practices based on the application of synthetic and organic fertilizers are compared. Two methods of harvesting, direct chip and whole rod, are analyzed. Two transport distances are evaluated; 50 km and 100 km. The scenario with the highest energy ratio will be determined. It is envisaged that the results of this study will help to establish the most environmentally friendly pathways for willow cultivation and harvest. As this study focuses on the production of biomass and transport to the end user gate it is thus considered a "cradle to gate" LCA (Figure 5.1).

The functional unit in this case is "1 GJ of energy contained in the willow biomass." Using a measure of energy contained in the feedstock allows the energy productivity of the system to be analyzed in comparison with other sources of fuel (Nemecek, Dubois et al. 2011, Goglio, Bonari et al. 2012). Total site preparation losses (ploughing and soil preparation) are assumed to be 1 tCO2/ha, according to Lanigan (2010). It is assumed that no net carbon sequestration occurs as the reference land use is grassland.

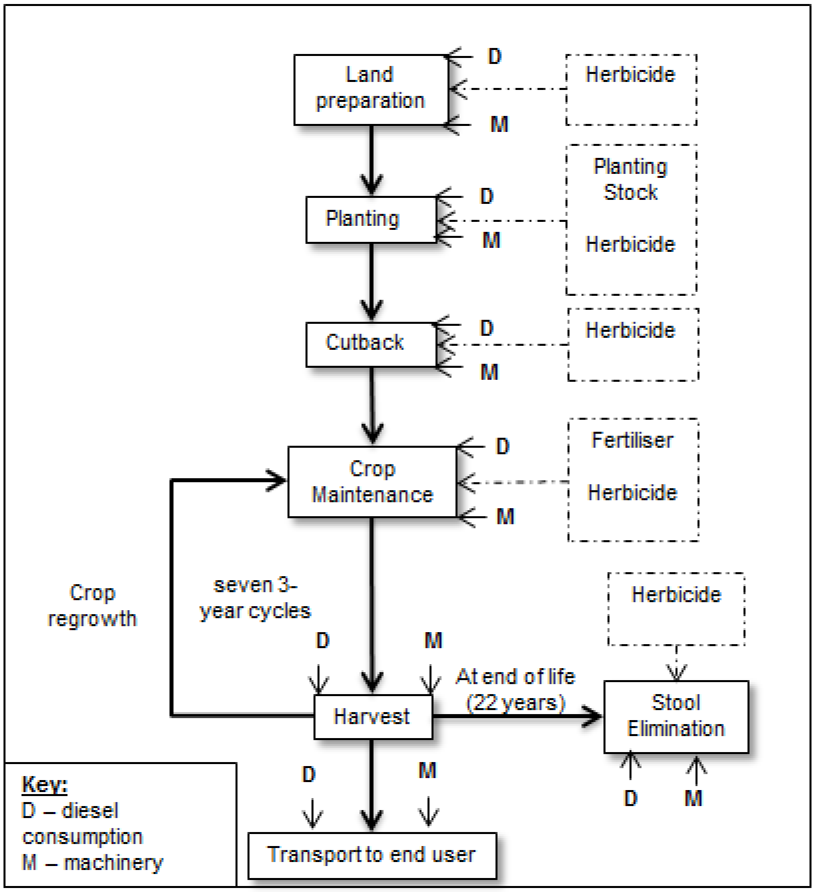


Figure 5.1. System boundary of willow cultivation. Dotted lines denote material inputs to the system.

The results clearly identify three important processes in the production chain; maintenance, harvest and transport. These three steps in the supply chain contribute the largest share of impacts to each of the impact categories. Maintenance, harvest, and transport, are repeated for every harvest cycle throughout the life cycle, while the other steps are only carried out once. Maintenance of the willow crop is highly energy intensive, with energy required for the manufacture of synthetic fertilizers but also in diesel consumption in the farm machinery used in fertilizer application. Willow harvesting and transport are also significant energy intensive processes with high consumption of diesel in the chipper harvester and truck engine respectively, contributing to the high energy demand (Figure 5.2).

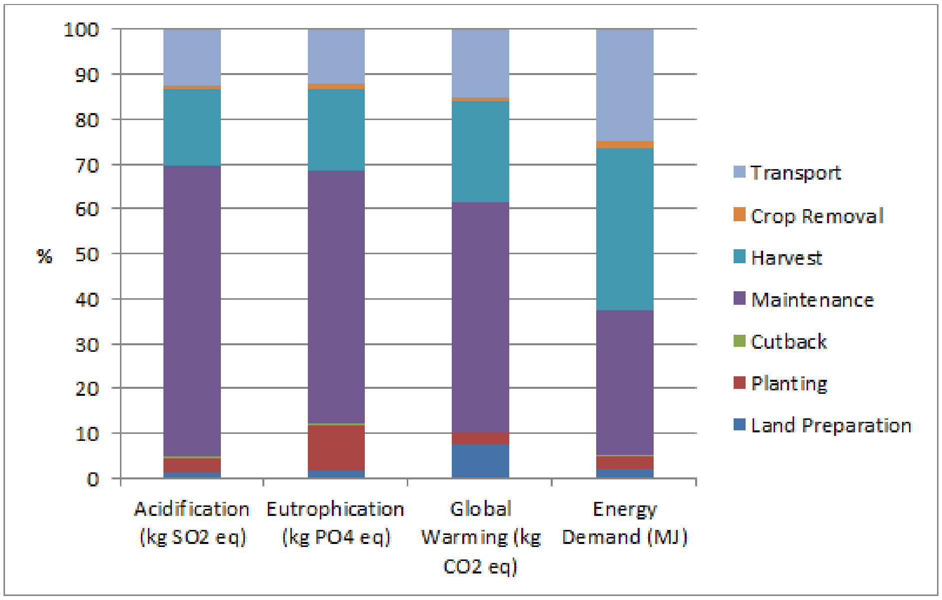


Figure 5.2. Percentage contribution of life cycle stages to each impact category for the base-case scenario.

Figure 5.3 demonstrates the energy requirements of each step in the life cycle. Figures in black indicate the energy demand associated with each individual step, while figures in green represent cumulative energy demand along the production chain. The final figures show that the cumulative energy required to produce 1 GJ of energy contained in the harvested willow.

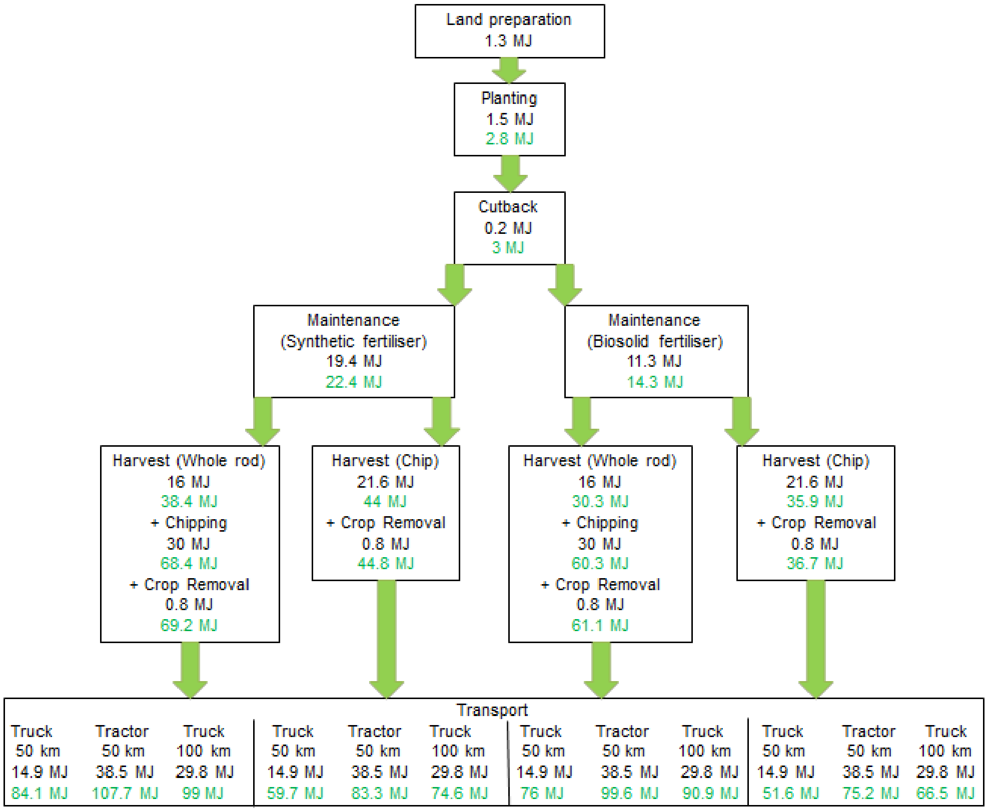


Figure 5.3. Energy flow diagram (per GJ of willow chip produced).

The production of synthetic fertilizers contributes significantly to each of the impact categories studied due to the energy and resources used to produce them. GHG emissions from synthetic nitrogen fertilizers also originate from N2O from the production process, and the technology utilized is an important factor in GHG emissions (Börjesson & Tufvesson, 2011). The application of biosolids to the crop as an alternative fertilizer has the potential to reduce these impacts through the utilization of a waste product to meet the crops nutrient requirements. Biosolid fertilisation removes the need for synthetic fertilizers which require significant energy inputs in manufacture.

The energy ratios of all willow chip scenarios are higher than both coal and peat which have an energy ratio of 2 and 5 respectively (Dones et al., 2007), implying that more energy is required to produce these fuels. Greenhouse gas emissions associated with willow production in all scenarios are lower than coal supply which emits approximately 12.28 kg CO2 eq per GJ of coal (Dones et al., 2007). GWP of peat provision is lower than the production of willow, as the harvesting of peat is the only process considered. Although combustion is outside the scope of this analysis, further GHG reductions would occur when comparing biomass combustion to fossil fuel combustion. The CO2 released during biomass combustion is approximately equal to the CO2 the biomass had accumulated from the atmosphere during its growing cycle, this convention is widely adopted in LCA studies of biomass-to-energy systems

(Cherubini et al., 2011). When compared to conventional fossil fuels, coal and peat, the willow biomass system performs favorably in terms of acidification and eutrophication potentials.

5.2.2 Woody biomass plantations for aviation fuel in Australia

While Australia currently produces considerable biomass from its agricultural and forestry systems, the total production falls well short of being able to sustain Australia's energy consumption, indicating that Australia's biomass resources will need to be directed towards strategically important energy uses. Although there is significant scope to increase the use of biomass, very little of it is currently used for bioenergy production. There are several reasons for this. First, there is a policy limitation: the need to better understand and address the interrelationship between carbon, water and energy to promote integrated outcomes for the natural and built environments within Australia has been already identified in government reports, and the integration of food, energy and water resources is a major issue facing Australia (PMSEIC 2010). Second there is a commercial limitation: while Australian broadacre farmers experienced declining terms of trade for most of the last 40 years with about a quarter not being profitable in recent years, this is not resulting in diversification away from grain cropping. For the coming five years the terms of trade and the area planted for cereal crops are projected to slightly increase. Farmers have adapted by increasing the scale of their operations and/or intensifying the production systems with increased innovation required to remain profitable. Recent studies have shown that the opportunity cost and perceived risk of displacing annual cropping with dedicated woody biomass plantings are significant impediments (Abadi et al. 2010). Third, delivery of environmental benefits have become unclear: the longstanding proposition that the problem of dryland salinity can be addressed by tree planting for biomass or other purposes, to increase water use in situ, has generally not shown discernible improvements at a catchment scale due to the limited extent of tree planting in salinized catchments. Revegetation as an integral part of other catchment actions is now recommended (Simons and Speed 2011).

Over the period 2007-14, the Future Farm Industries Cooperative Research Centre (FFI CRC)'s national R&D program addressed the challenge of how to improve the sustainability of Australian dryland agriculture through greater landscape scale water use with the introduction of new perennial pasture and forage species and cultivars. Woody tree cropping was researched for its potential to be a relatively small but strategically important part of land use change (provided it was profitable in its own right and the economic trade-off with annual cropping could be sufficiently mitigated).

With that work coming to the attention of aviation companies looking to options to reduce greenhouse gas emissions and to developers and users of biomass conversion technologies, the prospect of a more profitable value chain arose, namely integrating short-rotation biomass crops into existing mixed crop and livestock farming regimes for conversion to aviation and other biofuels, while providing broader environmental benefits including biodiversity protection. Australian airlines have shown strong interest in sustainable aviation fuels, since internationally the global aviation industry has agreed to greenhouse gas reduction targets with the International Civil Aviation Organisation (ICAO) resolving in 2010 to achieve carbon neutral growth from 2020; and the International Air Transport Association (IATA) setting a target of 10% alternative fuels by 2017 and a vision to build an aircraft that produces no emissions within 50 years.

In the 2011 Sustainable Aviation Fuel Road Map report to the Sustainable Aviation Fuel Users Group, CSIRO concluded that sustainable aviation fuel derived from biomass was "The only alternative fuel which can meet all of the environmental, economic and technical challenges…"; that "Australia and New Zealand are strongly positioned to incorporate sustainable aviation fuel into the aviation fuel mix. The scale of biomass production in the region is well matched to the aviation fuel industry's needs …";

“there are currently no significant supplies of sustainable aviation fuel anywhere in the world at this time. Establishing a local commercially viable supply chain is the major challenge needing to be addressed” so that biomass derived aviation fuel could supply 5% of Australian needs by 2020 and 50% by 2050. CSIRO identified short rotation coppicing tree species (for example eucalypts), via pyrolysis and catalytic upgrading as one potential source of aviation fuel (Figure 5.4). However, it estimated that jet fuel costs from coppicing eucalypts would be higher than other sources due to the low energy density of the feedstock and absence of cost effective harvesting equipment.

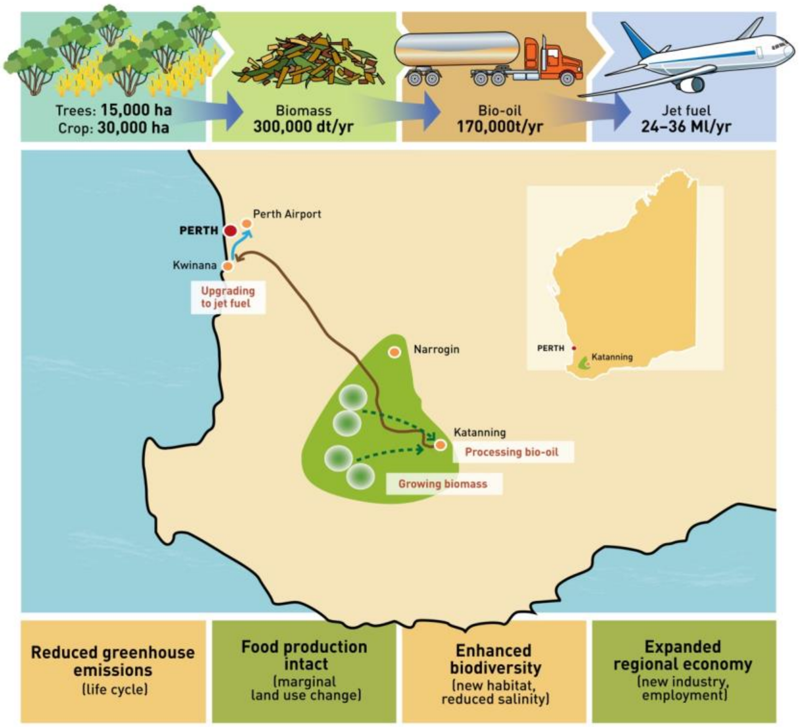


Figure 5.4. Integrated system for the supply of aviation fuel derived from mallee biomass based in the Great Southern region of WA.

The lignocellulosic system under evaluation in the Australian case is based on mallee eucalypt species native to Australia and is targeted at farming lower rainfall areas (300 – 700 mm/yr) in southern Australia that is generally known as the “sheep-wheat” belt. To evaluate the sustainability of this system, a case study was undertaken in the Great Southern region of Western Australia (400-600 mm/yr rainfall). Compared to other locations in Australia, significantly more R&D has been conducted here, with a mallee biomass-to-jet fuel business case and farmer cooperation providing reliable data for assessing the viability and sustainability of commercial supply chain development.

In brief, the results when evaluating the coppicing eucalypts as a biomass feedstock system for energy in Western Australia show that it is technically feasible to integrate this new production system into the overall farming enterprise. With the development of regional processing and support infrastructure, modelling shows that the system could be profitable for farmers and contribute strongly to regional economic development (Abadi et al. 2012). The capacity of Australian agricultural systems to produce biomass is limited by the relatively dry climate, indicating the need to direct the available biomass resources to strategically important energy uses such as aviation fuel supplies. Progress in developing the biomass resources required to support the development of regionally based bioenergy industries has been limited by the political and economic uncertainties currently facing the renewable energy industry in Australia. However, the strong understanding of the technical, economic and environmental aspects of the biomass production system indicates that there are strong development prospects when these uncertainties are resolved.

5.2.3 Switchgrass-to-ethanol production system in southeastern USA

Some perennial energy crops, such as switchgrass (*Panicum virgatum*) have considerable potential for being economically viable and environmentally beneficial in most crop producing regions of the US (Dale et al. 2011). While most perennial crops (like annual crops) attain their greatest yield under optimum growing conditions, switchgrass has several varieties that produce reasonably high and consistent yields on marginal upland, and its perennial characteristics allow production with minimal erosion on highly erodible land. Conversion of land from traditional annual crops to perennial energy crops results in significant soil improvements (Post et al. 2004). The reduction in disturbance of the soil due to no-till reduces wind and water erosion and allows soil aggregation and fungal-dominated organic matter cycling processes to re-establish. An additional benefit resulting from perennial crops is that root penetration increases soil porosity and infiltration and reduces compaction. Great increases in soil carbon occur on poorer quality sites; for example, conversion from annual to perennial crops resulted in soil carbon increases primarily in the upper 10 cm (Tolbert et al. 2002).

A recent (2008-2013) demonstration-scale East Tennessee switchgrass-to-ethanol production experiment provided a unique opportunity to examine a variety of environmental and socioeconomic data needed to analyze the overall sustainability of a dedicated cellulosic bioenergy crop production system (Figure 5.5). Switchgrass is native to Tennessee and has greater potential for consistent profit relative to corn production in the region than some other areas of the USA This case study was a demonstration project supported by the State of Tennessee. Farmers were awarded contracts at an incentivized rate while the biorefinery was under construction, thereby ensuring an adequate supply of switchgrass by the time the biorefinery came on line three years later. Heavy involvement in the project by University of Tennessee (UT) faculty and students led to optimized yields and to the production of a variety of datasets and publications that might not be as readily available in other settings. All of these context-specific factors should be considered when comparing the sustainability assessment of this pilot-scale switchgrass-to-ethanol experiment with other bioenergy systems in other settings.

In order to make the best use of available data, this case study of sustainability was limited to the feedstock production and logistics portions of the supply chain (i.e., field to biorefinery gate). Context-specific sustainability information was synthesized into qualitative ratings for the recommended indicators based on a combination of experimental data, literature review and expert opinion. A hierarchical decision tree framework was used to generate an assessment of the overall sustainability of this no-till switchgrass production system relative to two alternative East Tennessee business-as-usual scenarios of unmanaged pasture and tilled corn production.

The results in brief show that both local and watershed-scale benefits can be achieved by growing switchgrass in place of traditional crops in east Tennessee. Improvements in both water quality and farm profit can be realized by selection of locations for planting perennial energy crops. With a small decrease in projected profit, water quality can be improved, but the acceptability of this tradeoff to farmer-producers should be explored. Profit would be improved if there were a stable large-scale bioenergy production system and demand in the region. While focusing on individual targets can better achieve specific individual goals, this case study shows that a combination of goals can be addressed simultaneously.

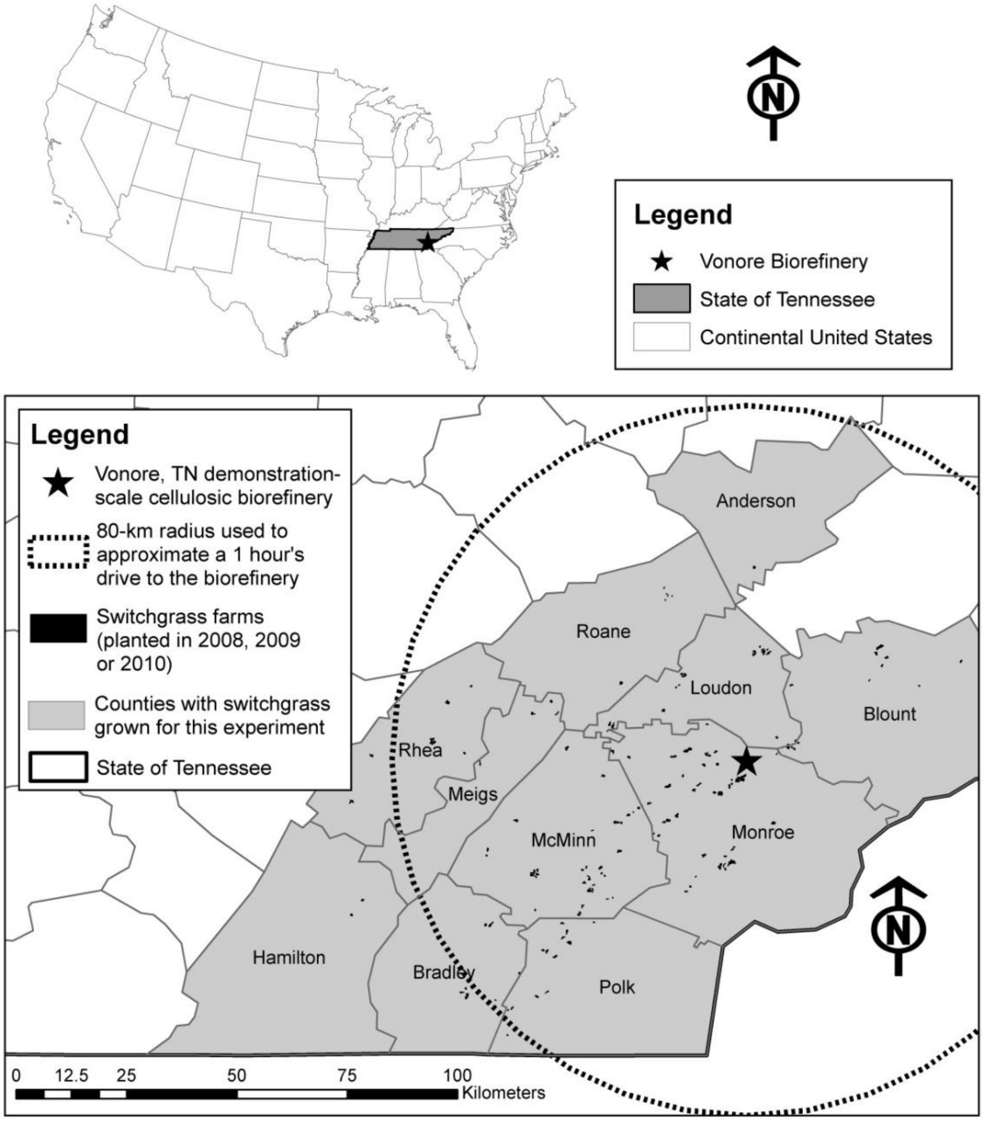


Figure 5.5. (a) Location the State of Tennessee and the Vonore biorefinery within the southeastern United States. (b) Location of the East Tennessee switchgrass-to-ethanol experiment, which included Tennessee farms within 80 km (50 miles).

Sustainability assessments will benefit from indicator measurements repeated over time and periodically incorporated into a sustainability evaluation framework (Figure 5.6). By viewing of policies and system interventions as experiments that need to be continuously monitored, updated and adjusted, more complete understanding of bioenergy production systems will be gained over time, and it will become possible to assign meaningful targets and weightings to the proposed suite of the Department of Energy sustainability indicators within different contexts. Conducting sustainability assessments of a variety of bioenergy feedstocks in diverse settings will enable the development of sustainable bioenergy crop management practices that meet multiple demands of stakeholders with understood tradeoffs (Figure 5.7).

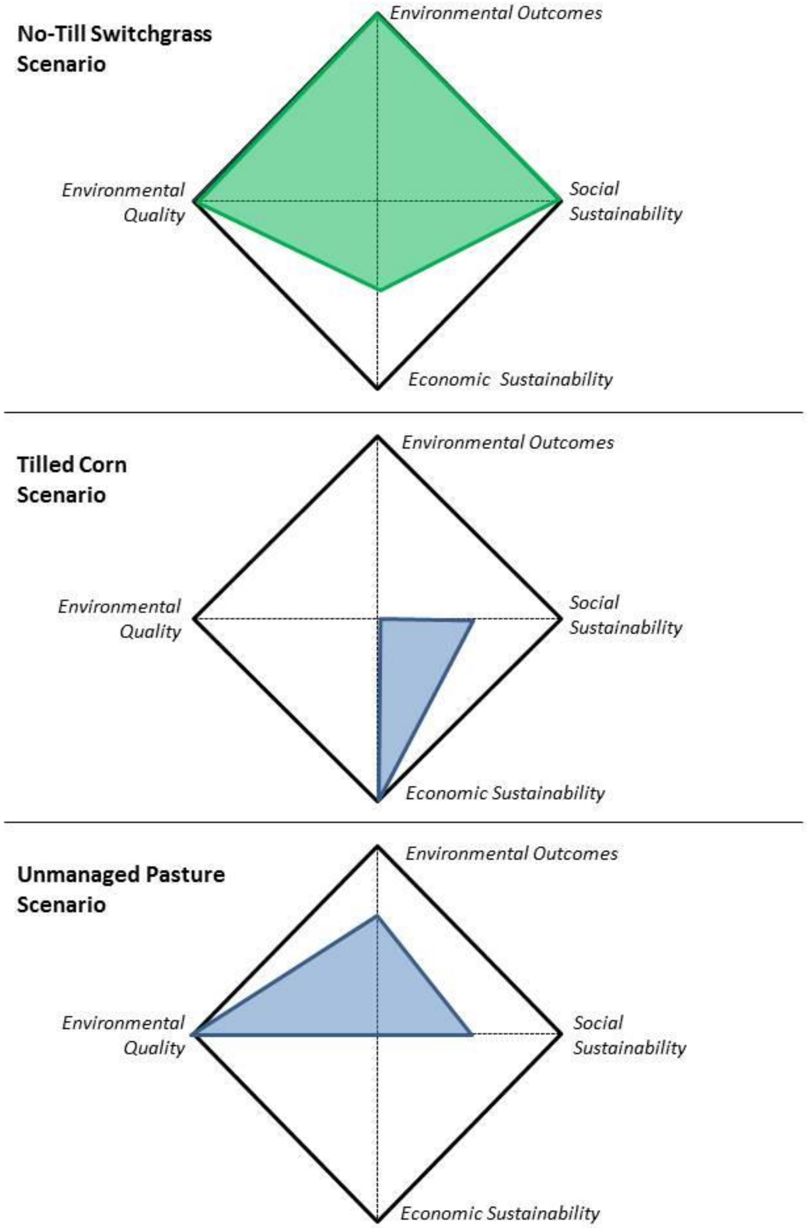


Figure 5.6. Aggregated sustainability ratings for three environmental quality categories (water quality and quantity, air quality and soil quality), three environmental outcome categories (biodiversity, greenhouse gases and productivity), three social categories (well-being, social acceptability and resource conservation) and three economic categories (energy security, profitability and external trade) for a no-till switchgrass scenario relative to likely alternative scenarios of tilled corn production and unmanaged pasture. The center points of the diamonds represent lowest possible sustainability ratings, and the outer edges of the diamonds represent highest possible ratings (McBride et al., 2011, Dale et al., 2013).

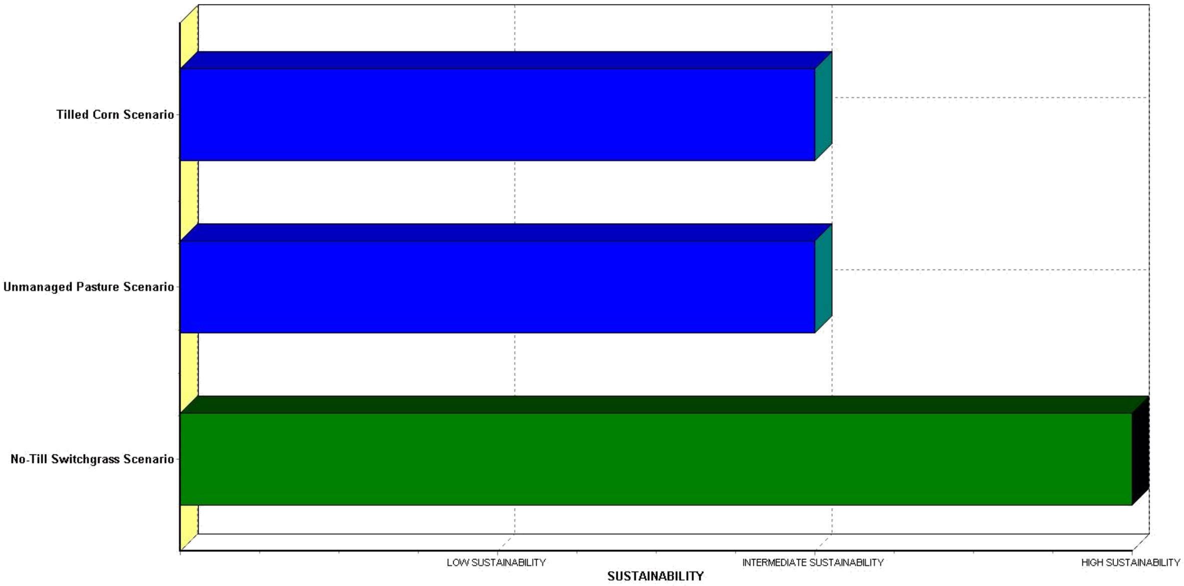
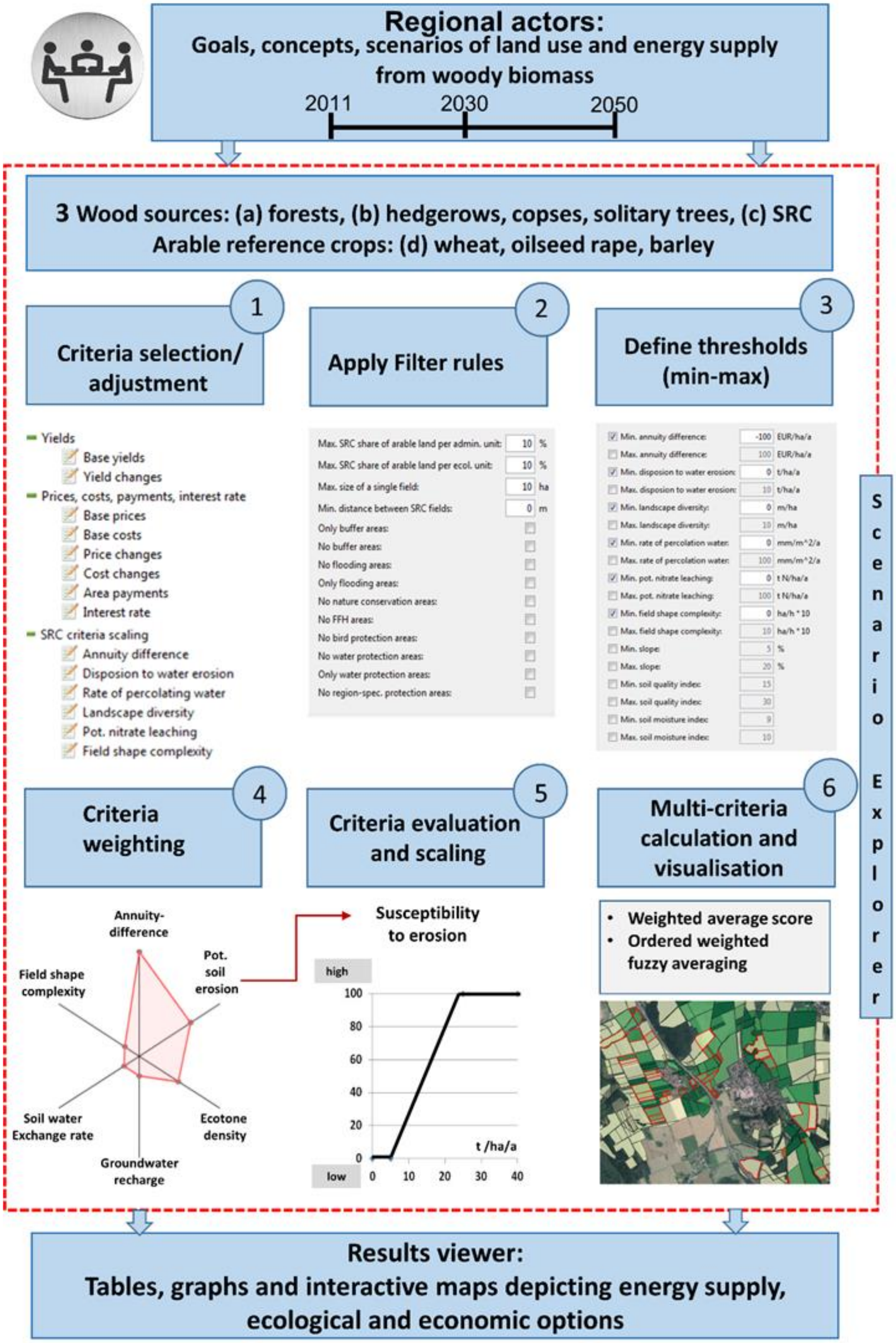


Figure 5.7. Overall sustainability determination of the switchgrass-to-ethanol case study for East Tennessee relative to two likely alternative scenarios of tilled corn production and unmanaged pasture. These ratings were based on an aggregation of 28 individual environmental and socioeconomic sustainability indicators aggregated within 12 categories.

5.2.4 Poplar short-rotation coppice for energy production in Germany

Climate protection is high on the regional political agenda in many German regions, and many regional governments have defined core actions via an “Integrated Climate Protection Plan.” In the case of the region of Göttingen, a major goal of this innovative and participatory approach has been to establish a roadmap towards a 100% renewable energy supply by 2050. This ambitious goal is only achievable with a substantial reduction in the energy demand. A considerable amount of renewable energy is expected to stem from biomass sources, and in most cases lignocellulosic crops such as short rotation coppice is not an option that is considered by local stakeholders. To link climate protection-related governance activities and a multidisciplinary view on ecosystem services and sustainable land use and to tackle stakeholder perceptions, a visualization tool was constructed to address land-use aspects in an interactive way. This tool, called the “Bio-Energy Allocation and Scenario Tool” (BEAST) was developed to bridge parts of this perception gap by investigating the Short Rotation Coppice (SRC) allocation impact on (1) ecosystem functions, (2) the economic return compared to specific annual crops, and (3) to allow scenario generation with the aim to combine renewable energy supply from woody biomass sources with aspects of sustainable land use (Busch 2012; Figure 5.8).



- Yields
  - Base yields
  - Yield changes
- Prices, costs, payments, interest rate
  - Base prices
  - Base costs
  - Price changes
  - Cost changes
  - Area payments
  - Interest rate
- SRC criteria scaling
  - Annuity difference
  - Disposion to water erosion
  - Rate of percolating water
  - Landscape diversity
  - Pot. nitrate leaching
  - Field shape complexity

Max. SRC share of arable land per admin. unit: 10 %
Max. SRC share of arable land per ecol. unit: 10 %
Max. size of a single field: 10 ha
Min. distance between SRC fields: 0 m
Only buffer areas: ☐
No buffer areas: ☐
No flooding areas: ☐
Only flooding areas: ☐
No nature conservation areas: ☐
No FFH areas: ☐
No bird protection areas: ☐
No water protection areas: ☐
Only water protection areas: ☐
No region-spec. protection areas: ☐

☑ Min. annuity difference: -100 EUR/ha/a
☐ Max. annuity difference: 100 EUR/ha/a
☑ Min. disposion to water erosion: 0 t/ha/a
☐ Max. disposion to water erosion: 10 t/ha/a
☑ Min. landscape diversity: 0 m/ha
☐ Max. landscape diversity: 10 m/ha
☑ Min. rate of percolation water: 0 mm/m^2/a
☐ Max. rate of percolation water: 100 mm/m^2/a
☑ Min. pot. nitrate leaching: 0 t N/ha/a
☐ Max. pot. nitrate leaching: 100 t N/ha/a
☑ Min. field shape complexity: 0 ha/h * 10
☐ Max. field shape complexity: 10 ha/h * 10
☐ Min. slope: 5 %
☐ Max. slope: 20 %
☐ Min. soil quality index: 15
☐ Max. soil quality index: 30
☐ Min. soil moisture index: 9
☐ Max. soil moisture index: 10

- Weighted average score
- Ordered weighted fuzzy averaging

Figure 5.8. Schematic of the overall structure of BEAST (Busch 2012).

The results in brief showed that in terms of economy, the majority of arable sites in the case study area (Figure 5.9) are not capable of providing a positive economic return for SRC under all circumstances.

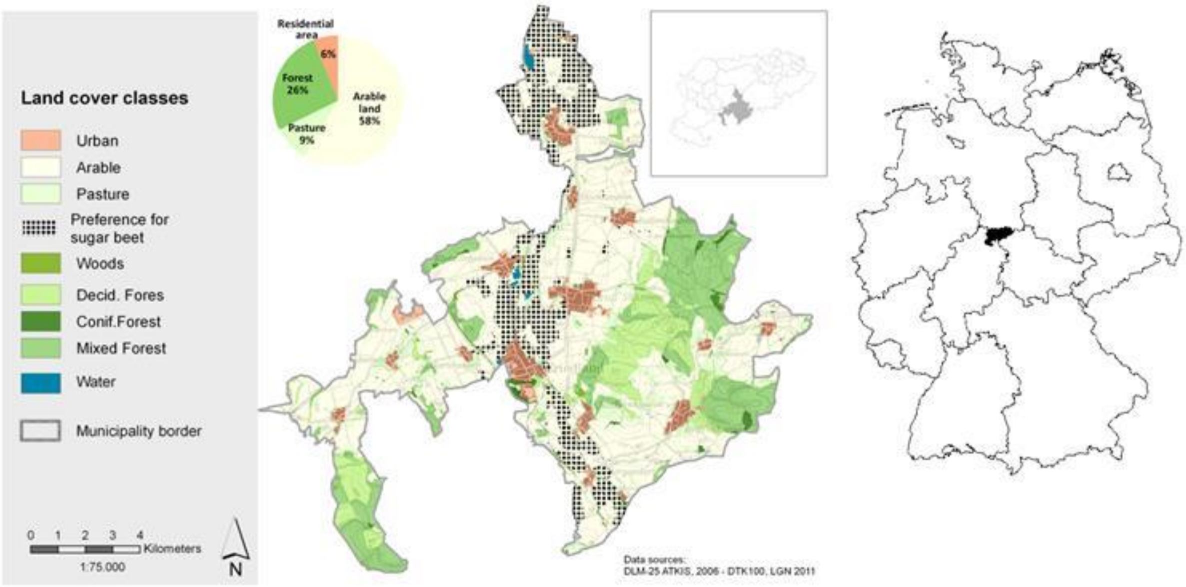


Figure 5.9. Study area: Landscape mosaic in the municipality of Friedland including preference sites for sugar beet-wheat rotations being excluded from SRC allocation assessment.

The tool shows that SRC outcompetes the reference crop rotation with a 100% probability in only 19% of the scenario cases (Figure 5.10). The minimum annuity difference a farmer could count on ranges between 0- 180 €. If farmers want to avoid the risk of a negative annuity difference under all circumstances, they have to stick to these 19% of arable land. The appropriate areas for SRC cultivation based on economic criteria compared to annual crops also have a positive effect to soil erosion, and since erosion protection is an environmental protection goal that is subsidized by government payments, minimum economic return would increase. This in turn, could be an additional incentive for a SRC implementation on these particular sites. On the other hand, SRC can have a negative impact on habitats that rely on high groundwater level or soil interflow from neighboring areas, and a potentially negative effect of SRC on surrounding habitats has to be carefully considered in combination with the positive effects such as soil erosion.

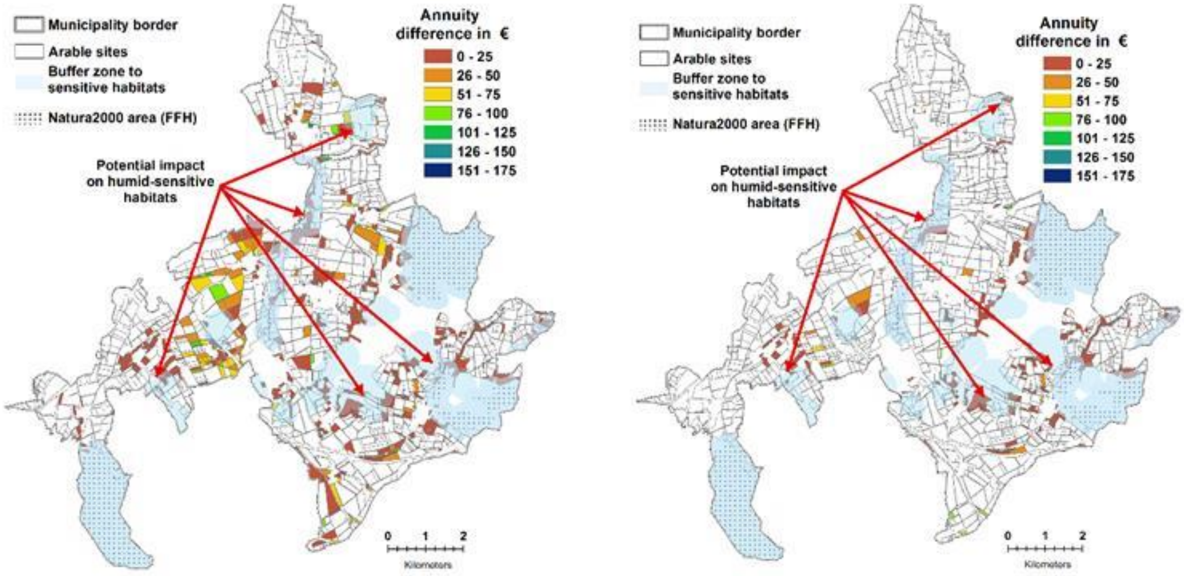


Figure 5.10. (a) economically competitive SRC sites, (b) economically competitive SRC sites that provide Cross Compliance-relevant erosion protection. Potential impacts on humid-sensitive habitats are separately illustrated.

5.2.5 Lignocellulosic plants as buffer zones in the USA

The US Energy Independence and Security Act of 2007 mandated aggressive biofuel production targets for the United States. Meeting those goals sustainably will require a new agricultural mindset that effectively balances concerns about economic viability with an ambitious focus on sustainability. Agricultural soil management practices—particularly fertilization—accounted for approximately 75% of USA nitrous oxide (N_2O) emissions in 2012 (USEPA 2014). Furthermore, runoff from fertilization of corn crops (a large component of biofuel energy balance) is a significant source of non-point water pollution, and a significant source of economic loss. There is a concern that bioenergy crops grown in systems mimicking the current large scale agricultural production may also increase the already significant impacts of commodity agriculture on water, air and wildlife. These concerns call for proactive thinking and development of a holistic vision for a future where a novel, integrated landscape design optimally produces goods and services to satisfy societal needs for food, feed, energy, fiber, as well as environmental services, ecological health, human well-being and quality of life. One possible approach to develop this vision is to plan at the landscape level the use of land and water resources so that the most fitting crops and agricultural practices are used in the parts of the landscape that are most suited to them and to use specific crop traits to gain beneficial environmental services. For instance, this approach would encourage the cultivation of main grain crops on the most fertile land while perennial crops are grown where the productivity of main food/feed crops would be lower. Alternatively moisture tolerant bioenergy crops would be grown where the land is more vulnerable to flooding or ponding water, or deep rooted perennials would be grown where land is more susceptible to nutrient leaching or erosion. This approach relies heavily on landscape design concepts and is increasingly gaining momentum under the US Department of Energy (ANL 2014).

Landscape design, like conservation science, relies heavily on features such as buffers (Figure 5.11). Conservation buffers are strips of vegetation placed in the landscape to influence ecological processes and provide a variety of goods and services. Riparian buffers, buffer contour strips or filter strips and windbreaks are examples of conservation buffers. Buffer strips, together with wetlands, are a common tool used in conservation practices and are the subject of substantial programs by the USA government (Doering 2007). In these programs, vulnerable or ecologically relevant land is not used for cropping purposes but instead is set aside for filtering water runoff and/or providing other ecosystem services. Overall, there is a broad recognition of the crucial role of riparian land and buffer strips in regulating nitrogen cycles and, more generally, water quality. Studies have also indicated that nitrous oxide emissions in buffer systems are a function of nitrate availability, soil conditions such as pH, temperature and moisture, microbial communities and plants growing in the system (Hefting et al. 2003, Kim et al. 2009).

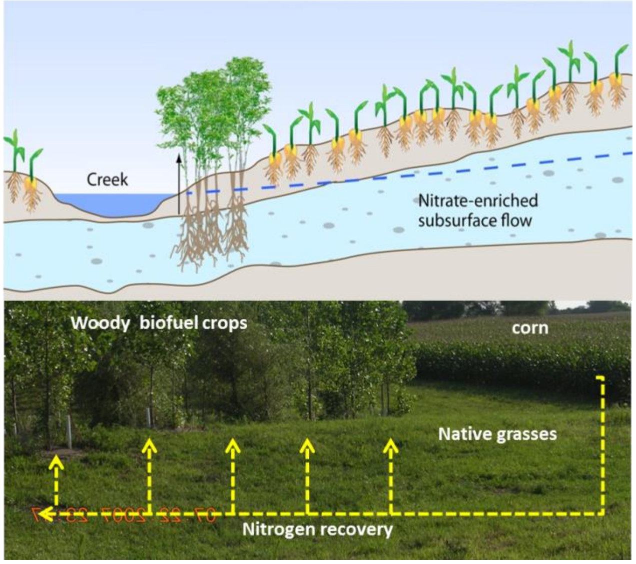


Figure 5.11. Conceptualization of bioenergy buffer function within a corn field.

In government-supported conservation buffers, removal of biomass via harvesting is usually not allowed. While this ban is considered beneficial to protect the environmental and ecological function of very fragile land, there are other cases where harvesting biomass for energy may provide an attractive income to farmers while at the same time delivering valuable environmental and ecological services. Harvesting biomass may also provide a way to remove nitrogen from the buffer area via the harvested vegetation, thus maintaining buffer function. Establishment of buffers however can remove some land from the current cropping system, thus creating an economic dilemma for farmers. It is clear that while many designs are possible and effective, the valuation of the water quality improvement may contribute to the adoption of buffers by providing support in case the bioenergy crop does not fully compensate the farmer.

Experiments have been conducted to test the environmental performance of buffers and their social and economic sustainability (Ssegane et al., 2015), and while more study is needed to definitively assess the benefits and constraints of buffers as nutrient-scavenging bioenergy producers, a few conclusions have been derived (Figure 5.12). First, not all buffers are created equal: while riparian buffers receive the lion's share in conservation applications, not all locations bordering a stream benefit from having a riparian buffer, and contour buffers may be more appropriate. Soil characteristics and easily available yield maps can be instrumental in positioning the bioenergy crops in locations that target the most vulnerable areas and those areas that can be converted to bioenergy in a cost-effective manner. Second, when deploying bioenergy crops in vulnerable areas, existing management practices developed for business-as-usual cropping may need to be reassessed to minimize impacts to water. Use of cover crops, double cropping and caution in the use of chemicals should be considered to address the long period of little ground cover during the bioenergy crop's establishment time and the management of weeds. Third, research needs to be conducted in establishing minimum patch size and field geometries that would allow farmers to easily subscribe to landscape-based bioenergy cropping and that would provide optimized logistics. Fourth, scaling up this approach to the watershed scale is necessary to integrate scientifically sound data with logistic choices and local interests. Finally, feedback from farmers and farm operators and consultants is essential in designing landscape solutions that are acceptable and likely to be adopted in farms (Figure 5.13).

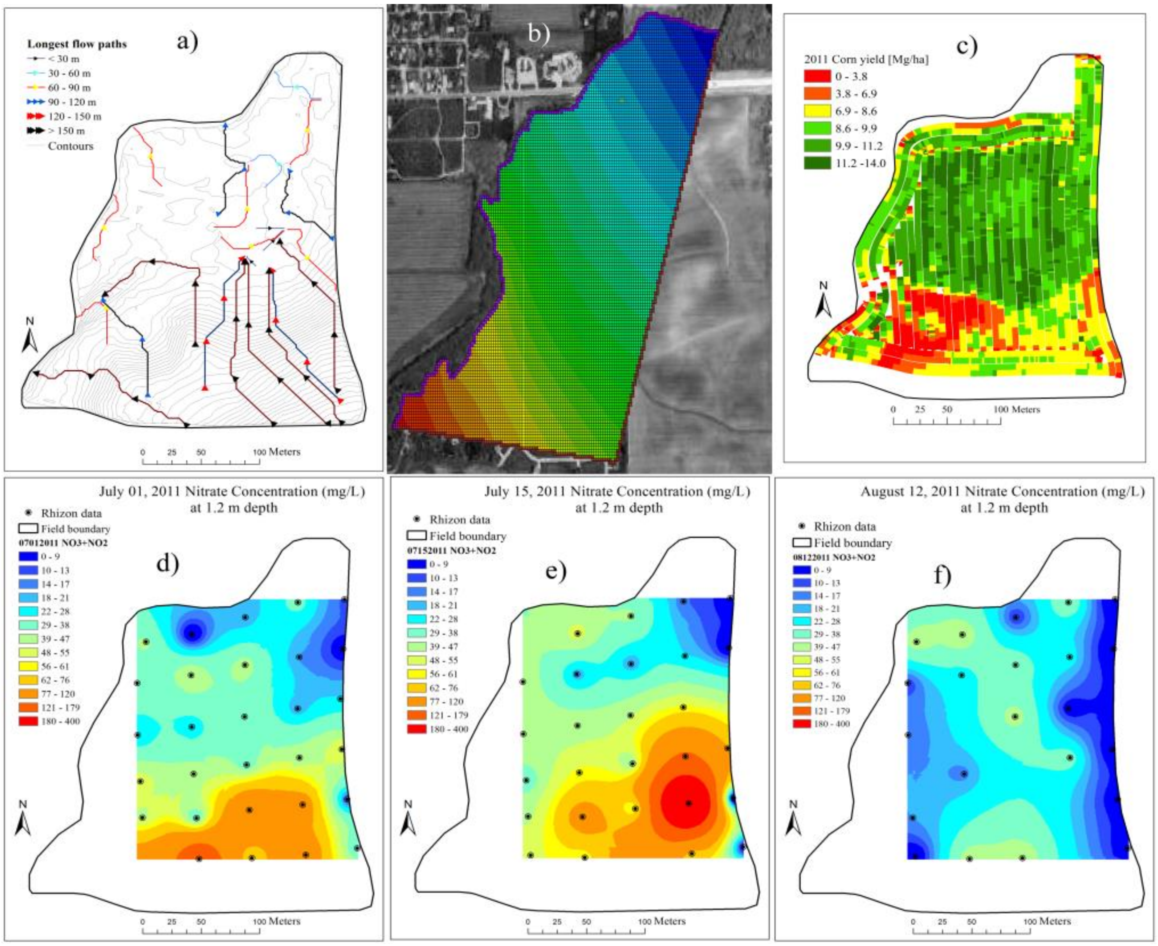


Figure 5.12. Baseline results: terrain analysis, groundwater flow direction, yield map, and nitrate plume at 1.2m below ground surface at different times over the spring/summer season of 2011.

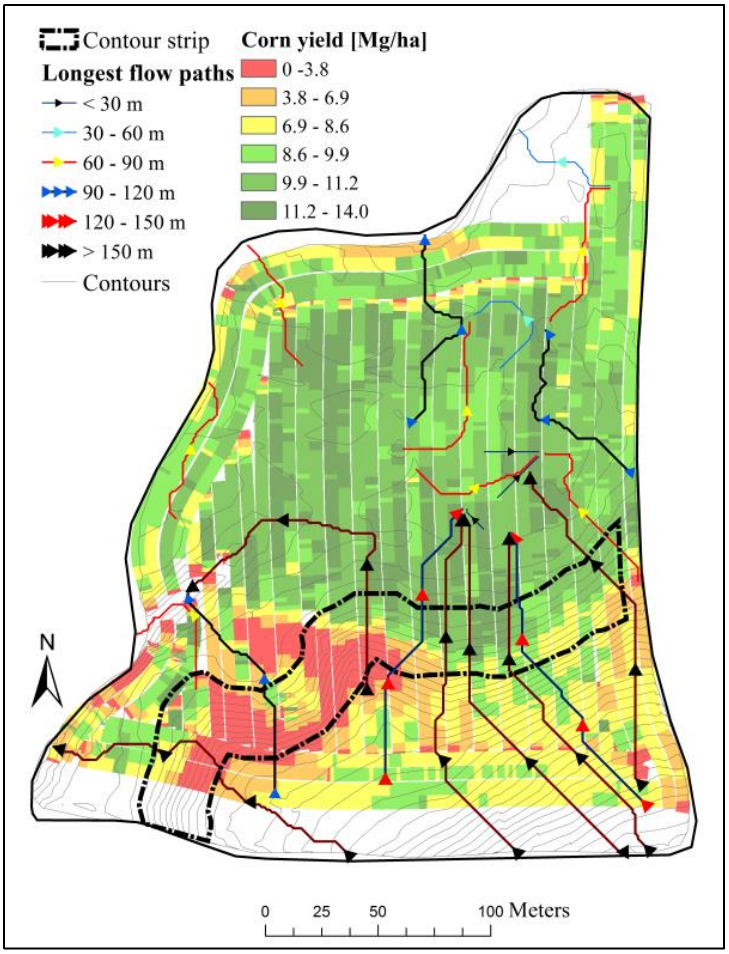


Figure 5.13. Final design of the contour buffer.

5.2.7 Recycling of sludge and wastewater to short-rotation coppice with willow for bioenergy in Sweden

Future lignocellulosic bioenergy systems in agriculture should be "land-efficient," and the amount of energy produced per hectare should be the highest possible. Also, unless other incentives exist, cultivation practices for such systems should be more profitable for the farmer than those for food crops, to motivate farmers to grow bioenergy crops. With the current relative low energy prices and the relative high food prices, few bioenergy systems can compete and be adapted by farmers in large-scale. Therefore, multifunctional systems producing besides biomass for energy additional dedicated ecosystem services should be adapted in order to promote the establishment of lignocellulosic crops in agricultural landscapes. The application of society's residues rich in nutrients, e.g. municipal wastewater (Figure 5.14) or sewage sludge (Figure 5.15) to short rotation coppice plantations with willow (SRCW) has been identified as an attractive method to meet all the above, achieving environmental and energy goals, while simultaneously increasing farmers' income (Dimitriou and Rosenqvist 2011).

Figure 5.14. View of a municipal wastewater plant in Enköping, Sweden, with water storage ponds and (behind the ponds) the willow fields that are used as vegetation filters. The photo is taken from the roof of the heat and power plant that uses the locally produced biomass (Photo: Pär Aronsson, SLU).

SRCW is a non-food, non-fodder energy crop that offers advantages such as high evapotranspiration rate and tolerance to anoxic conditions and heavy metals, and therefore is considered appropriate for such applications. Using sewage sludge and wastewater to fertilize SRCW offers environmental advantages and economic profit to farmers cultivating SRCW due to reduced fertilization costs and increased biomass produced.

Figure 5.15. Willow SRC field applied with sewage sludge (Photo: Pär Aronsson, SLU).

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The economic profit of the farmers can be substantially higher if this method used effluent from wastewater treatment plants instead of other alternatives. Even if a small amount of the P entering the wastewater treatment plant is applied to SRCW in the form of wastewater and/or sewage sludge, the area agricultural land planted to SRCW could be markedly increased, leading to a considerable increase of renewable energy from lignocellulosic crops. See Table 5.1 (modified from Dimitriou and Rosenqvist 2011).

Table 5.1*. Theoretical estimations of land required if all available sewage sludge (ss) and wastewater (ww) would be applied to SRC, and consequent increases of the renewable energy amounts in different European IEA Bioenergy Task 43 countries.*

	Population (millions)	SRC area to be fertilized with all available ss (1,000 ha)	SRC area to be fertilized with all available ww (1,000 ha)	Arable land surface with SRC fertilized with ss (%)	Arable land surface with SRC fertilized with ww (%)	Energy produced from SRC if all ss applied (PJ)	Energy produced from SRC if all ww applied (PJ)
EU-27	495.13	35673	1505	34	1.4	5636.3	309.2
Denmark	5.45	436	18	18	0.7	62	3.4
Finland	5.28	422	17	19	0.8	60.1	3.3
Germany	82.31	5931	250	50	2.1	937.0	51.4
Ireland	4.31	259	11	26	1.1	49.1	2.7
Italy	59.13	3550	146	50	2.1	673.1	36.9
Netherlands	16.36	1179	50	111	4.7	186.2	10.2
Sweden	9.11	505	23	19	0.9	103.7	5.7
UK	60.85	3654	150	60	2.5	692.7	38

5.3 SYNTHESIS

The above-mentioned examples gave a good idea of the different context-specific opportunities and constraints for sustainable lignocellulosic cropping systems for production of biomass and other ecosystem services. Each of these potential opportunities was context-specific meaning that they could be only achieved in particular places due to the existence of a driver for more biomass for energy, with a simultaneous implementation of good management practices and a supportive social and political environment. To generally describe the opportunities provided by the different lignocellulosic cropping systems, it is worth comparing them and drawing parallels with general barriers and opportunities for bioenergy. These are briefly summarized in the following.

5.3.1 Barriers

5.3.1.1 Policy

Sustainable energy is often a general policy aspiration, but its definition is not always clear. While policy should be about managing risks and promoting opportunities, it often becomes more about promoting certain interests. The tradeoffs inherent in specific policy recommendations are often not clear. Policy barriers related to bioenergy in general and lignocellulosic crops in particular are often specific to individual countries.

5.3.1.2 Cost of a new energy system

The cost of developing and deploying any new energy system (such as the ones based on lignocellulosic biomass) is high, and those new costs are not always compared to the large amount of existing and past financial support provided to fossil energy or conventional bioenergy production systems. Lignoellulosic bioenergy technologies need time to mature, and maturation should result in reduced costs via operational experience and scale.

5.3.1.3 Unlevel playing field

All energy ventures are not at the same starting point today. The knowledge infrastructure and investment for fossil energy are huge compared to renewables. Fossil fuels represent the “natural capital” of a nation and its future generations. The many opportunity costs that are expended when fossil fuel capital is extracted and burned are not reflected in fossil fuel prices. Nor are the actual costs for pollution and potential costs to society of future climate change. Fossil fuels were created using areas many times as large as current production areas, and using energy from thousands of years of planetary effort is not accounted for in a life-cycle assessment; yet all costs associated with renewable fuel production (also valid for lignocellulosic crops) are counted. Hence an across-the- board comparison of current one-time costs and benefits of different energy options is not entirely valid but is often the only information that is available.

5.3.1.4 Public perceptions

In many arenas the common viewpoint is that bioenergy coming from agriculture is bad for the environment and competes with food. More transparency of information about fossil fuels and bioenergy is needed. Often the comparison between bioenergy and fossil fuels is not done in an even manner because fossil fuel information is proprietary, or the accidents occur far away, or the indirect impacts associated with fossil fuel exploration and use, regardless of how great they may be, are assumed to be insignificant. Effective stakeholder participation requires engagement of all key stakeholders and sharing of information about the implications across all steps of the supply chain.

5.3.1.5 Easy access to relatively cheap fossil fuels

The attraction of inexpensive and readily available fossil fuels continues to influence political and economic activities to the detriment of biofuels and other clean, advanced renewable energy technologies.

5.3.1.6 Too optimistic about costs and timetables

Overly optimistic timetables about bioenergy production have resulted in the perception that lignocellulosic bioenergy is always “five years away.” After hearing this claim too many times, the investment community, policy makers, and public do not believe that bioenergy is a realistic option. The use and dissemination of “good examples” that work in reality is a necessity to further implement more bioenergy projects based on lignocellulosic crops.

5.3.1.7 Lack of Infrastructure

Bioenergy infrastructure is immature or wholly lacking in many areas. Most of the vast potential in natural resources remains stranded far from the ports and centers of demand. There are unique challenges in the collection, transportation, shipping, and logistics of lignocellulosic energy crops, but while production costs at field scale for many lignocellulosic crops, residues and wastes are relatively low and seem to be globally competitive, the delivered cost for bioenergy production pathways often increases dramatically due to added costs associated with poor infrastructure and limited logistic capacity. The lack of integration of bioenergy with other parts of the production system stymies optimal use of existing infrastructure.

5.3.1.8 Need for new investment

Investments in science and industry are required for the bioeconomy to grow. Investments have fallen since the financial crisis of 2008. More recently, the lignocellulosic industry faces difficulties competing with subsidized fossil energy and existing production of other biofuels such as demolition wood, household wastes, and others. Credit is more restricted and the many uncertainties about future policies and markets undermine additional investment needed to reach a critical economy of scale required for a competitive lignocellulosic crop management and industry.

5.3.1.9 Uncertainty about future demand and price structure

Related to policy uncertainties and poor infrastructure is the lack of certainly about future demand and prices for bioenergy. Doubts about the viability of future bioenergy markets also affect interest in investment.

5.3.1.10 Sustainability concerns

Sustainability concerns remain an obstacle, particularly for European markets and on topics that social and environmental organizations continue to highlight as issues such as labor rights, food security, deforestation, biodiversity, and low yields. While there are examples of bioenergy projects compromising social and ecosystem services, as shown above, there are also many counter-examples that provide insights on how to deploy bioenergy systems sustainably. This concern calls for reiteration of the need for full transparency of the costs and benefits related to other energy options.

5.3.2 Solutions for supporting the mobilization of sustainable agricultural residue chains in different operational environments

5.3.2.1 Replacement of non-renewable fossil energy

The widespread use of fossil fuels is contributing to global climate change and may be the greatest environmental issue of this century. Replacement of non-renewable fossil energy with renewable bioenergy (also from lignocellulosic crops) can help mitigate these problems and simultaneously conserve fossil energy resources for future generations.

5.3.2.2 Enhanced energy security

Energy security is enhanced when sources are diversified and can be accessed locally within a region or country. Similar to food security, energy security can be considered from a perspective of household energy requirements in terms of the availability, affordability, accessibility, and awareness of clean, reliable energy sources to meet daily needs, or it may refer to issues of economic security, national supplies and the lack of dependence on foreign sources to support national security goals. While access to inexpensive energy is essential to modern economies, uneven distribution of energy supplies leads to vulnerabilities. Fossil fuel reserves are located in many places around the globe, but their large-scale commercial extraction occurs in only a few regions making other regions/nations dependent on imports. As such, the transport of coal, petroleum and natural gas around the world is a huge industry and involves some security risks. For those countries that have appropriate climate and soils to support agriculture that can produce lignocellulosic crops, sustainably produced biomass from them can be transformed into bioenergy. Such locally available feedstock sources provide opportunities for enhanced energy security in regions able to produce their own bioenergy rather than relying on imports.

5.3.2.3 Reduced risk of catastrophes

Locally produced bioenergy, e.g. from lignocellulosic crops, has a reduced risk of catastrophes as compared to fossil energy. Risks associated with bioenergy include traffic accidents associated with transport and the possibility of fires where biomass is stored. Fossil fuels have demonstrated significant risks for catastrophic accidents that include large spills that pollute rivers, lakes and marine environments at the point of drilling; transport accidents involving tanker trains, trucks and pipelines; drilling and mining accidents involving explosions and loss of life, as well as fire and storage risks.

5.3.2.4 Creating incentives to improve management of renewable resources

Policies to develop bioenergy have gone hand-in-hand with efforts to define, measure and assess the sustainability of production systems. Progress towards more sustainable production is unlikely to occur in the absence of incentives. Bioenergy could help spur investment in deployment of more sustainable practices and serve as a model for other sectors and agriculture. Aspirational sustainability goals for bioenergy systems could change the way that sustainability is understood and addressed. Many places around the world where natural resources of land and water are available and where the climate is suitable for biomass production have been previously cleared and are now underutilized, mismanaged or burn frequently. Having bioenergy-based incentives for improved resource management could have far-reaching implications.

5.3.2.5 Stable jobs

Biomass production from lignocellulosic crops and processing to produce biofuels can benefit rural communities by increasing employment opportunities and expanding the tax base that supports community services. Expansion of the bioeconomy could provide jobs in rural areas where unemployment is often high. Furthermore, while many jobs in fossil fuel extraction are difficult and risky (e.g., coal mining and work on oil rigs), replacing fossil fuels with bioenergy would substitute fossil-based jobs with bioenergy jobs.

5.3.2.6 Keeping land in agriculture

Bioenergy deployment would provide additional incentives for keeping land in agriculture as compared to pressure for development. The ecosystem services provided by agricultural land as compared to urban or suburban development would thus be retained.

5.3.2.7 Improving environmental conditions

Biomass production can improve environmental conditions compared to “traditional” agriculture or forestry or other energy options. These improvements require good management practices that are specific to the particular context. Water quality can be enhanced where lignocellulosic bioenergy is grown and harvested as compared to traditional agriculture, for some of these perennial plants require less fertilizer and their large rooting systems can reduce water flow and erosion. Biodiversity can also benefit by use of lignocellulosic plantings as compared to traditional agriculture. Protection of biodiversity requires adherence to good management practices such as avoiding harvest during nesting periods. Carbon benefits accrue under some circumstances with bioenergy production. For example, carbon accumulates as long as the wood-producing land remains in forests and any resulting bioenergy replaces fossil fuels over one hundred years or more. Because photosynthesis consumes CO_2 and perennial crops can accumulate biomass and soil carbon, biofuel production and utilization can be carbon-neutral and even reduce net atmospheric CO_2 emissions.

5.3.2.8 Increased food security

Increased production and income associated with lignocellulosic biomass for biofuels have the potential to improve food security. Food security depends largely on household access to services and ability to pay. Providing additional markets for rural producers, incentives to invest in the infrastructure needed to grow and transport bioenergy feedstocks, and stabilizing prices at levels that create incentives for local production, are all expected to increase food security. Food price volatility contributes to food insecurity and is reduced by having multiple products and market options from a commodity.

5.3.2.9 Existing infrastructure, knowhow and technologies

Building bioenergy systems on existing agriculture infrastructure and technologies reduces costs and makes it easier for land managers to adopt new practices. Often existing equipment can be used or modified for use in bioenergy production. Lignocellulosic supply chains are more likely to survive the challenges of early market development if they can be supported by existing industries.

5.4 CONCLUSIONS

Various lignocellulosic crops in agriculture can produce biomass for energy as well as provide additional ecosystem services and environmental, social and economic benefits. Such positive impacts can be optimized if such systems are designed in a way that takes into account research results on several of these issues. For wider implementation, it is not only necessary to conduct research that prove the sustainability of these systems and alter on implement them in larger scale, but also to communicate them in a way that would cause decision-making to be in favor of stable and long-term policy incentives that support lignocellulosic crops, which for the time being is not generally occurring in much of the world.

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6

CULTIVATION OF GRASSLANDS AND PASTURES IN BRAZIL

6.1 INTRODUCTION TO CASE STUDY

Grasslands and pastures cover a large part of the global land area, and significant areas are suitable for bioenergy feedstock production. The use of grasslands and pastures for this purpose has attracted increased attention because (i) land productivity improvements free up large grassland and pasture areas for other uses, and (ii) the greenhouse gas (GHG) emissions associated with establishing bioenergy plantations on such lands are lower than when forests are converted. At the same time, there are several challenges associated with the use of grasslands and pastures, including the risk of biodiversity losses, water resource competition, and deforestation due to indirect land use change (iLUC). It is therefore essential to learn from experiences in locations where large grassland and pasture areas have been converted to bioenergy plantations.

This case study focuses on the Brazilian experience, and especially the cultivation of sugarcane for ethanol on former pasture land, an option that could be promoted in several other countries where sugarcane can be cultivated. We describe sugarcane ethanol production conditions and prospects for expansion, governance aspects and factors affecting market demand for Brazilian ethanol, and the interaction between the sugar and ethanol markets. Lignocellulosic and other feedstocks are also briefly discussed, especially palm oil biodiesel, which has received increased attention in Brazil in recent years. The influences of water resource availability and use are discussed in a dedicated Section 6.2.4 because of their strong influence on the prospects for bioenergy feedstock production on grasslands and pastures around the world.

6.2 ANALYSIS OF BIOENERGY AND FEEDSTOCK PRODUCTION SYSTEM

6.2.1 Factors affecting market demand

The production of ethanol and sugar from sugarcane in Brazil have been linked since the 1920s, when ethanol was first considered to be a feasible co-product from frequent surpluses of sugarcane (Walter et al. 2013), leading to the first mandate for a 5% ethanol blend in Brazilian gasoline in 1931. In 1975, motivated by the negative impacts of oil imports on Brazil's balance of payments after the 1973 oil crisis, the National Alcohol Program (Proalcool) was launched with a target to replace 20% of the gasoline consumed in the country with ethanol. From 1975/1976, ethanol production increased more than 20-fold, reaching almost 12 x10^9 liters in the 1985/1986 season (MAPA 2013). The sharp decline in oil prices combined with the increase in national oil production led to a period of stagnation for Proalcool that lasted until 2002/2003, when escalating oil prices renewed interest in ethanol fuel. The market launch of Flex Fuel Vehicles (FFV) in 2003 motivated consumers to start using ethanol, which had become very cost-competitive with gasoline despite the absence of subsidies. Production increased from 12.5 x10^9 liters in 2002–2003 to 27.7 x10^9 liters in 2008/2009, when the economic crisis, low gasoline prices to Brazilian consumers despite high oil prices, and a series of extreme weather events, along with poor field management, contributed to the end of this period of growth. Ethanol production costs increased, mainly because of low sugarcane yields and higher fertilizer and fuel costs. At the same time, the government had kept the gasoline prices constant at the pump since 2005 aiming to hold down inflation (Jank 2013), in spite of escalating oil and gasoline prices in the international markets.

During these periods of growth and stagnation of ethanol production and consumption, the economic competitiveness of Brazilian sugar production improved due to reductions in feedstock cost. The deregulation of the sugar/ethanol sector in the 1990s spurred the rapid growth of sugar exports, as shown in Table 6.1.

Table 6.1. Evolution in sugarcane, sugar, and ethanol production. Source: MAPA (2013).

Harvest season*	1975/76	1985/86	2002/03	2008/09	2011/12
Sugarcane production (Mt)	68.3	223.2	316.1	572.7	560.5
Ethanol production (ML)	556	11,932	12,485	27,681	22,701
Sugar production (Mt)	5.9	7.8	22.4	31.5	36.0
Sugar exports (Mt)	<1	-	13.5	20.8	24.9

* From April 1st to March 31st the following year

Thus, in parallel with the enormous growth of ethanol production since 1975/1976, sugar production increased six times and sugar exports went from near zero to 24.9 Mt, nearly half of the international market. Brazil became not only the largest sugarcane ethanol producer, but also the main sugar producer and exporter, so that in the medium to long term the ethanol and sugar markets acted independently.

With the deregulation of the power sector in 1999, the industry was able to increase resource efficiency and afford the premium for more efficient equipment required to generate electricity as an additional product with guaranteed revenues. The electricity for export doubled between 2006 and 2012 to 30 x10^3 GWh, primarily during the seasons of low hydropower production in North Brazil (Chum et al. 2015).

Lately it appears that, because of the importance of Brazil in the international sugar market and of ethanol in the domestic market, a strong linkage was created between the prices of raw sugar in the New York Mercantile Exchange and the hydrous ethanol parity prices (price of ethanol converted in sugar equivalent) in Center-South Region (LMC 2015). The anhydrous ethanol prices are indirectly connected with these two markets because the distilleries can normally vary the production ratio of hydrous to anhydrous. Yet product demand is affected by the blending rate (kept in the range of 18 to 27% for anhydrous ethanol by government controls), and the hydrous ethanol pump price is capped by the gasoline pump prices and is also affected by the raw sugar prices in the New York Mercantile Exchange. These complex supply–demand relationships can be used to adjust the production profile of the three products to maximize profits (or minimize losses). This is aided by the fact that around two-thirds of the sugarcane is processed in mills that produce both ethanol and sugar and have the flexibility to change the production profile by plus/minus 20% of either product (CONAB 2013). One serious external and uncontrolled cause of strong impacts on the performance and volumes of the three product markets is international sugar prices, which are normally affected by climate variations in important producing countries, and the instability of Asian producers' demand–supply equilibrium (LMC 2015).

Public policies and legal frameworks directly impact the three products of sugarcane and their relationships with markets. Policy-driven biofuel demand, such as in the USA and EU, can stimulate investments, but uncertainties about future biofuel markets impact on investment interest. Domestic ethanol demand is becoming difficult to predict due to lack of government mandates clarifying the role of ethanol in the Brazilian light duty vehicles (LDV) fuel matrix. This is further complicated by the fact that the participation of the FFVs in the LDV fleet has reached 60% and is increasing, creating direct competition between gasoline and hydrous ethanol in the filling stations. The equivalence ratio between hydrous ethanol and gasoline (E27) is estimated to be 0.70, meaning that when the ethanol price is above 70% of the price of gasoline, the consumer will tend to choose the fossil option to fill the FFV tank. The government projection of 2023 transport fuel demand indicates a gap equivalent to 26 $x10^9$ liters of gasoline to be filled by gasoline, ethanol (39 $x10^9$ liters of ethanol), or a combination of both (MME 2015). Yet today's oil refineries cannot produce this amount of low-octane blend, and there are limitations in the gasoline supply infrastructure (port terminals, storage tanks, and pipelines). The ethanol sector does not seem inclined to invest in expansion of production capacity to meet the projected demand due to the uncertainty in the future market and evolving regulations.

In Brazil, the internal and external sugar markets are totally deregulated and steered by free market forces; the growth on the internal market is relatively easy to predict, but the international market has several players in different regions of the world and is subject to rules and conditions (such as weather) that make market prediction a challenge. Nevertheless, the international market represents close to 70% of Brazilian sugar sales and has a strong economic impact.

Finally, the interaction of the sugar and ethanol markets and its dependence on gasoline prices demonstrates the need to reduce ethanol production costs to the levels of the recent past. This would require significant additional investment that can only occur if public policies provide market stability as they did the past. The situation is becoming even more complex because the low margins for sugar and ethanol are magnifying the importance of surplus electricity sales to the grid. The increasing scale of new mills improves conditions for electricity cogeneration, and delayed hydropower projects open opportunities for other renewable energy development, mainly wind and biomass. Several barriers (e.g., the requirement that power generators assume the full cost of grid connection) inhibit development, but experience shows that resource planning integrating biopower with other power resources benefits both power producers and Brazilian people (Chum et al. 2015). In spite of these challenges, the installed capacity at bioenergy mills recently passed the 10 GW mark, with a significant part of that capacity being available for sale.

6.2.2 Supply

6.2.2.1 Prospects for sugarcane expansion in Brazil

The recent revision of the Brazilian Forest Act, the main legal framework for protection of native vegetation on private land, has changed the context for mobilizing bioenergy supply chains in Brazil by altering the relative importance of public and private governance systems addressing nature conservation and agricultural production. The Forest Act revision resulted in less protection of native vegetation, and less stringent requirements for restoration planting and assisted regeneration of natural ecosystems on agricultural land. The legislation also includes a comprehensive Environmental Rural Registry that facilitates monitoring and surveillance by government and civil society. Whether conversion of natural ecosystems will take place depends on how public and private governance together balance the purposes of protecting natural ecosystems and agricultural production (further discussed in Section 6.4.2).

Figure 6.1 shows how land suitability for biomass production (right) and protection of native vegetation (left) vary across Brazil. The greater the ratio of protected vegetation to total native vegetation, the greater share of native vegetation is protected under legal command and control regulatory frameworks on private or public land. It can be expected that conversion of native vegetation into biomass cultivation will be more prevalent where a high proportion of land suitability overlaps with a lower degree of protection of native vegetation (i.e., low ratio on left map), unless protection is enhanced by incentives and other regulations that complement governmental directives.

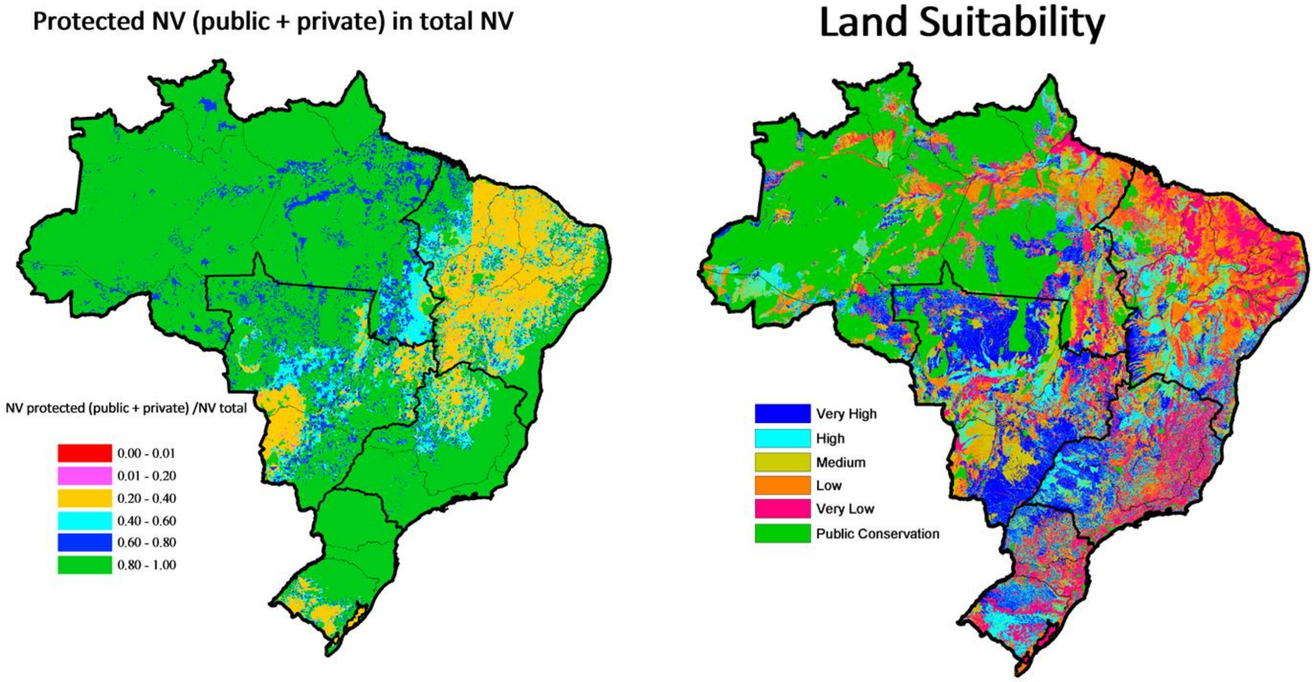

Figure 6.1. Ratio of protected native vegetation to total native vegetation (left), and land suitability classes and public conservation (right). Reprinted with permission from Sparovek et al. (2015a). Copyright 2005 American Chemical Society.

Table 6.2 shows three scenarios for allocation of legally available land to cropland, pasture and native vegetation.[1] (Figure 6.7 shows the land governance structure in Brazil.) The land allocation is guided by criteria commonly considered in frameworks for agro-ecological and economic zoning, which are frequently used[2] to fulfil legal demands and meet requirements set by the Ministry of Environment at the state level.

In the ***Conservation scenario***, marginal lands are set aside for restoration of native vegetation, in line with the Brazilian experience of abandoning such agricultural land after the consolidation period; high

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[1] The assessment made used a spatially explicit land use modelling framework for Brazilian agricultural production and nature conservation that considers: (i) the Atlantic Forest Law, (ii) the revision of the Forest Act, (iii) the Amazonian land-titling initiative “Terra Legal,” (iv) the spatial distribution of agricultural land suitability, (v) technological and management options, and (vi) the effects of market driven regulations. The model was used to analyze three scenarios, one prioritizing conservation objectives, one prioritizing production objectives, and one that is neutral between those objectives.

[2] Users include investment agencies such as the Brazilian development bank for sugarcane investments, governmental agencies engaged with policy design, and organizations engaged with sustainability certification.

yielding cropping systems expand on very high suitability lands currently under native vegetation and pastures; and beef production increases through productivity improvements on pastures situated on high and medium suitability lands. Native vegetation prevails in the entire Legal Amazon region, Pantanal, steep areas along the Atlantic Forest biome, and climatically marginal areas of the north-eastern and southeast semi-arid regions. The remaining pasture area occupies larger parts of Rondônia and Roraima, south of Acre a larger extension of North of Tocantins, Maranhão and Pará, and moving south, a more patchy distribution on the lower suitability classes associated with steep slopes. Crops dominate on legally available lands in most of the Cerrado biome and northwest of Rio Grande do Sul. In total under this scenario, native vegetation increases by about 30% and cropland increases 1.5 times, and pastureland decreases more than 40%.

Table 6.2. Land allocation on legally available land for the three scenarios (+ denotes application of productivity enhancing measures in favorable locations). Reprinted with permission from Sparovek et al. (2015a). Copyright 2005 American Chemical Society.

Current land use / land cover		**Suitability for agriculture**		**Scenario-specific land allocation**		
Type	**Mha**	**Class**	**Mha**	**Conservation**	**Neutral**	**Production**
Natural vegetation (NV)	114	very high	9.4	CR+	CR+	CR+
		high	18.8	NV	PA+	CR+
		medium	23.8	NV	PA+	PA+
		low	31.0	NV	NV	PA+
		very low	30.7	NV	NV	NV
Pasture (PA)	166	very high	38.4	CR+	CR+	CR+
		high	35.3	PA+	CR+	CR+
		medium	28.4	PA+	PA+	CR+
		low	30.4	PA	PA	PA+
		very low	33.2	NV	NV	PA
Crop (CR)	77	very high	30.2	CR+	CR+	CR+
		high	19.0	CR	CR+	CR+
		medium	9.6	CR	CR	CR+
		low	9.1	CR	CR	CR
		very low	9.2	NV	CR	CR
Resulting land allocation for the three scenarios (Mha)			**NV**	**147**	**95**	**31**
			PA+	**64**	**71**	**85**
			PA	**30**	**30**	**33**
			CR+	**78**	**132**	**189**
			CR	**38**	**28**	**18**

In the ***Production scenario***, there is no restoration of native vegetation; pasture expands on native vegetation land, and pasture production is intensified even on lower suitability land; and native vegetation and pastures on higher suitability lands are converted to improved croplands. Native vegetation prevails on available land in the semi-arid northeastern Caatinga biome and steep slopes or extremely poor soils of the Cerrado biome and Pampas, but is replaced by pasture or cropland in the other areas. Crops dominate landscapes, while pastures show a more patchy distribution occupying the lower suitability areas surrounded by crops. Agronomic intensification on lower suitability lands potentially increases impacts associated with soil erosion and environmental pollution. In total, more than two-thirds of native vegetation on legally available lands is converted to agriculture; cropland increases 2.7 times, and pasturelands decreases about 30%.

In the ***Neutral scenario***, conversion of native vegetation to improved cropland and pasture is partly balanced by restoration of native vegetation on pastures situated on very low suitability lands. Native vegetation expands on available land, only excluding areas in some states with continuous prevalence of very high and high suitability land where crops occupy larger portions of the rural landscape. Pastures expand over the medium and low suitability land throughout Brazil, seldom dominating the landscape but rather introducing variation in landscapes dominated by either cropland or native vegetation. In total, native vegetation is reduced by 17%, cropland increases 2.1 times, and pastureland decreases by about 40%, with roughly 70% of the remaining pastureland placed under intensified use.

One important finding of the above scenario analysis is that ***Brazilian agricultural production can grow without extensive conversion of forests and other native vegetation***.

To illustrate, municipal level analyses made across the whole of Brazil showed that relatively modest productivity improvements[3] would allow a doubling of the current crop output (excluding sugarcane) and maintaining — or even increasing by 20% — beef production, while leaving enough suitable and legally available land for sugarcane production to support an ethanol industry five to seven times its current size, corresponding to an ethanol output at some 135-190 x10^9 liters[4]. About 20 Mha would be used for sugarcane production in this scenario. For comparison, 63.5 Mha was mapped as suitable by the Brazilian government, after taking into account the need to protect the Amazon, conserve biodiversity, and avoid conflict with food production (Souza et al. 2015). Much of this mapped land consists of pasture, largely in the Cerrado region, with low stocking density. Planting sugarcane on these lands without indirectly causing extensive conversion of native vegetation elsewhere would require improvement of the remaining pasture to support an increase in the number of head per hectare.

As a second illustration, analyses show that palm oil production on some 40-60 Mha of suitable land can support biodiesel production corresponding to approximately 10% of the current global diesel demand without impinging on protected areas or causing direct LUC emissions (i.e., carbon stock would increase or be roughly unaffected where oil palm is planted). Almost all of this area is currently in agriculture, with roughly three-quarters in pasture (15–25% of all pasture in Brazil) and one quarter in cropland (10-15% of all cropland). Thus, oil palm expansion would certainly affect food production and the outcome depends on how an expanding palm oil production integrates with existing agriculture production — and agriculture producers — and how existing production responds to the increasing land claim for oil palm. It can be expected that the present land use patterns would change (e.g., extensive cattle production would likely decrease) and that agricultural land use would become more intensive in areas where land prices rise. Again, productivity gains as illustrated in the above scenario analysis can support production increases that avoid conversion of native vegetation. However, a combination of incentives and effective protection of native vegetation is likely required to achieve productivity gains that moderate area expansion. The pressure on remaining native vegetation can be expected to increase in areas where palm oil production capacity and associated infrastructure become established. (See Figure 6.2.)

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[3] Average cattle productivity increases 50 and 100% on low and high suitability pastures, respectively, and crop yields increase on average 20 and 50% on low and high suitability lands, respectively.

[4] Assuming ethanol output at 80 and 120 liters per Mg of sugarcane (first- and second-generation technologies).

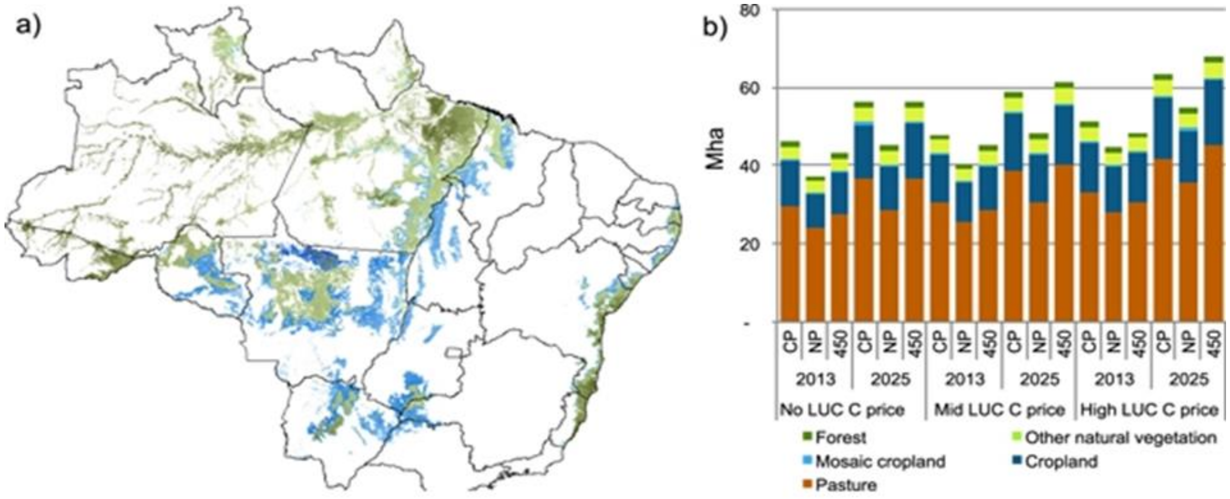

Figure 6.2. Areas where establishing new oil palm plantations would (1) be profitable for producers; (2) increase carbon stock; and (3) not impinge on land protected by law. The map shows the spatial distribution of such areas in 2 out of 18 scenarios: those with the lowest potential (green) and highest potential (green + blue). Darker colors indicate higher yields. The diagram shows quantified results for all scenarios divided into six land use/cover classes. The scenarios combined the three 2012 WEO scenarios, Current policies (CP), New policies (NP), and 450 ppm, with three different levels for LUC carbon price development[5] to form nine scenarios. Two different establishment years (2013 and 2025)

6.2.3 Global outlook

The bioenergy mobilization potential associated with grasslands and pastures depends on the evolution of a multitude of social, political, and economic factors, e.g., nature protection measures, land tenure and regulation, diet, trade, and technology. Illustrating how critical parameters influence the prospects for cultivation of grasslands and pastures, Wirsenius et al. (2010) modelled scenarios for the global food system up to 2030 and showed that relatively modest productivity improvements for livestock production systems, above improvement projections by the UN Food and Agriculture Organization, could reduce the agriculture land use in 2030 by roughly 500 Mha. Compared to agriculture land use around year 2000, the improved agriculture land use in year 2030 required roughly 250 Mha less land; about 95 Mha more cropland was needed in 2030 but the pasture area decreased by 340 Mha.

In a scenario where 20% of the per-capita consumption of ruminant meat (beef and mutton) is replaced by an equal amount (in terms of kg per capita per year) of pork and poultry, agricultural land use was 725 Mha smaller than around the year 2000; the cropland area was roughly 60 Mha larger, but the pasture area was about 780 Mha smaller. Thus, ***released pasture land could accommodate the cropland expansion and at the same time reduce the conversion pressure on natural ecosystems by providing ample room for bioenergy expansion***.

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[5] The LUC carbon levels used for year 2013 correspond to the average carbon price on voluntary carbon markets ($22/t C: "mid") and the modelled carbon price on the EU Emissions Trading Scheme (ETS) market as presented in the WEO ($64/t C: "high"). Carbon price levels diverge over time and are assumed to grow faster in the scenarios with more stringent climate policy (i.e. 450 ppm). By 2025, in the 450 ppm scenario, the highest carbon price used was $249/t C. Oil palm cultivation is found to be unprofitable on 80-90% of the Brazilian forest area at $125/t C.

Table 6.3 shows estimates by Fischer et al. (2009) of technical biomass supply potential associated with rain-fed cultivation on unprotected grasslands and woodlands (i.e., forests excluded) when land requirements for food production, including grazing, have been considered at 2000 levels. Fischer et al. (2009) also emphasized the critical influence of productivity improvements on the numbers presented in Table 6.3 and concluded that the technical biomass supply potential could increase from 171 to 288 EJ per year (globally) if livestock grazing areas were freed up for additional bioenergy production by intensification of agricultural practices and pasture use. As shown below, bioenergy mobilization potentials as well as prospects for agricultural production in general are very sensitive to how management of water resources evolves into the future.

Table 6.3. Global and regional grassland/woodland areas and technical potential of rain-fed lignocellulosic plants on unprotected grassland and woodland, when land requirements for food production (crop cultivation and grazing) at year-2000 levels has been considered (Chum et al. 2011, Fischer et al. 2009).

Region	Total grassland and woodland area	Protected grassland and woodland area	Unproductive or very low-productive areas	Technical potential when also excluding grazing land in use		
	(Mha)	(Mha)	(Mha)	(Mha)	Av. yield* (GJ/ha/yr)	(EJ/yr)
N America	659	103	391	111	165	19
Europe & Russia	902	76	618	122	140	17
Pacific OECD	515	7	332	97	175	17
Africa	1086	146	386	275	250	69
S&E Asia	556	92	335	14	285	4
L America	765	54	211	160	280	45
ME&N Africa	107	2	93	1	125	0.2
World	**4605**	**481**	**2371**	**780**	**220**	**171**

* Assuming an energy content at 18 GJ Mg per year, dry matter basis. Agronomically attainable rain-fed yield levels calculated for grid cells of 5-minute latitude/longitude resolution, based on climate, soil, terrain data, currently available cultivars, adequate applications of nutrients, and adequate chemical control of pests, disease and weeds.

6.2.4 Influence of water resource management, irrigation, and water use efficiency

While abundant water availability provides opportunities for biomass production in some regions, water scarcity in other regions seriously restricts land use, and demand for bioenergy may add to the growing pressure on water resources. Water scarcity has been identified as a potential major obstacle for bioenergy expansion, but it is also recognized that bioenergy demand opens up new opportunities to adapt to water-related challenges and to improve the productivity of water use (Berndes 2002, 2008; Service 2009). The net effect on the state of water depends on the characteristics of the crop (e.g., leaf area index), and land use and water management associated with the bioenergy systems put in place, compared to the previous situation.

Figure 6.3 shows how water availability and irrigation strategies can determine the biomass mobilization potential on lands presently not used for agricultural production (excluding forests, wetlands, protected land, and land with severely degraded soils). As can be seen, the influence of irrigation patterns is large, and crop choice further amplifies the variation between scenarios. While lignocellulosic short-rotation woody plants show a greater response to irrigation, the higher land and water productivity of herbaceous plants allows larger total biomass production. The results do not reflect economic costs of expanding irrigation infrastructures and cultivating areas where infrastructure currently is limited. Yet, the results clearly show the large influence of water availability and management, aspects that have received relatively little attention in previous studies of the prospects for bioenergy mobilization.

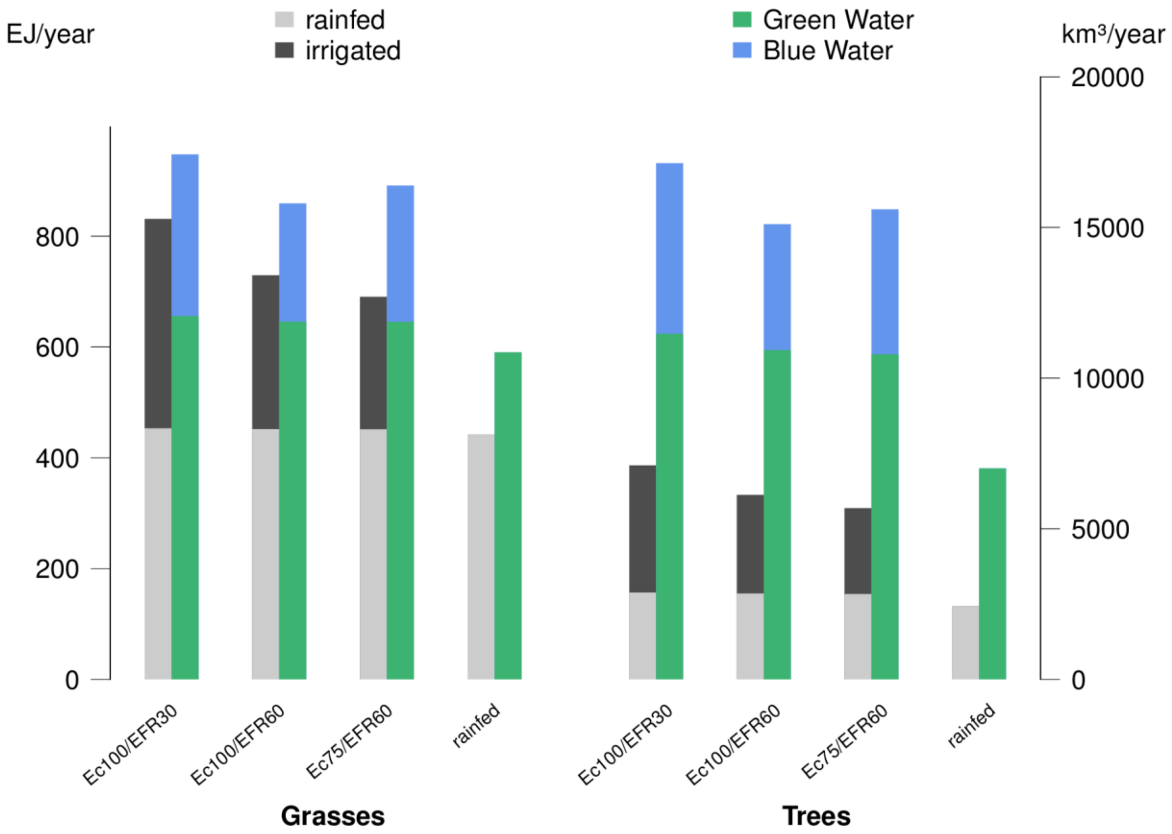

Figure 6.3. Primary biomass supply potentials (grey-black bars, left y axis) and associated water consumption (green-blue bars, right axis) when grasses and trees are cultivated under scenarios including varying efficiency with which water is conveyed from source of supply to the field (conveyance efficiency, E_C: 75 or 100%) and varying environmental flow requirements (EFR: 30 or 60% of available water flows are not available for cultivation). The water is used on a first-come, first-served basis. Based on Jans et al. (2015).

Complementary to global modelling, investigations at local and regional levels show that biomass can be cultivated in plantings that offer benefits from the perspective of water (Berndes et al. 2015, Dimitriou et al. 2011). For example, some plants can be cultivated as vegetation filters for treatment of nutrient-bearing water (e.g., pretreated wastewater from households and runoff from farmland). Soil-covering plants and vegetation strips can also limit water erosion, reduce evaporating surface runoff, trap sediment, enhance infiltration, and reduce the risks of shallow landslides (see also Chapter 5). Furthermore, expanded cultivation of crops with greater heat and drought durability and greater water-use efficiency (e.g., Agave, Opuntia, Jatropha) into semi-arid, abandoned, or degraded agricultural lands may avoid competition with food and feed crops (Cushman et al. 2015, Gelfand et al. 2013, Qui et al. 2014, Ostwald et al. 2015). Plants that are cultivated in multi-year rotations can also utilize rain falling outside the growing season for conventional crops. Thus, there exist opportunities for improving water productivity in agriculture and alleviating competition for water and pressure on other land use systems.

However, these opportunities need to be carefully assessed from a water balance perspective (Berndes 2002, Dallemand and Gerbens-Leenes 2013, Otto et al. 2011, Watkins et al. 2015). For example, the use of marginal areas with sparse vegetation for establishing high-yield bioenergy plantations may lead to substantial reductions in downstream water availability, requiring management of trade-off between upstream benefits and downstream costs (Garg et al. 2011). Availability and competing uses of water resources can therefore critically influence the feasibility of cultivating grasslands and pastures, and strategies for expanding bioenergy feedstock cultivation on such lands need to be integrated into wider basin level planning that accounts for other water needs, including environmental flow requirements.

6.2.5 Economic competitiveness relative to a reference energy production system

The Brazilian sugarcane ethanol supply chain represents a mature system that is already competitive in some markets having policy and regulatory support, e.g., in Brazil, EU, and USA. Revenues from co-products (energy and food/feed) and technology advances in conversion (second-generation ethanol) can further improve cost competitiveness. The competitiveness also depends on international sugar prices, e.g., in 2010–2011 a combination of factors[6] resulted in nearly doubled estimated average production cost, making Brazilian ethanol roughly 30% costlier to produce than corn ethanol in the USA. Modelling indicates that Brazilian sugarcane and sugar costs are to a higher degree than USA corn cost influenced by ethanol production (Chum et al. 2014), in part because of lower utilization of capital equipment during harvest season for sugarcane. The utilization of existing capacity could be increased by processing complementary sugar crops. See also Section 6.2.7.

Brazil is currently a minor producer of palm oil, but large areas are suitable for oil palm cultivation, and Brazil has launched several initiatives seeking to promote and regulate expansion of oil palm involving, e.g., technical assistance to farmers, agricultural and industrial incentives and credits, sustainability monitoring and evaluation, land titling, protection of traditional peoples, and social inclusion (Villela et al. 2014). To illustrate the competitiveness of biodiesel from palm oil, the range of fossil fuel prices in the 2012 IEA WEO scenarios (IEA 2012) would allow profitable oil palm cultivation over very large areas, including areas where it displaces forests and other native vegetation and causes LUC emissions. In the absence of governance preventing high LUC emissions, profitable biodiesel production at the scale of present global diesel demand is possible, but the associated LUC emissions would corresponds to almost half of the USA cumulative emissions from fossil fuels since preindustrial times (Englund et al. 2015). However, as was shown in Section 6.2.2, the economic potential is large also when high LUC emissions are avoided, since there are large areas of suitable land outside forests. Figure 6.3 shows a situation where high carbon prices discourage high LUC emissions and where palm oil biodiesel production roughly corresponding to 10% of the current global diesel demand would be profitable.

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[6] Including global weather-related problems affecting the production of sugar, low sugar stocks, and a rise in the sugarcane feedstock price caused by record-high sugar prices (Chum et al. 2014).

6.3 OPERATIONAL ANALYSIS

6.3.1 Current supply chain technology and system integration

Some modifications in Brazilian sugarcane production and processing have resulted from the requirement to phase out cane burning prior to harvest in several important sugarcane cropping states, including São Paulo. A shift from manual to mechanical harvesting and planting is underway, which has brought both benefits and challenges. Soil compaction, ratoon damage, and increases in sugarcane impurity levels reduce crop yields and sugar losses, as well as increasing maintenance costs in the mills. Continuous improvement in the mechanization technology is mitigating the negatives impacts, but the technology is not yet optimized for the more complex feedstock. On the positive side, air pollution and GHG emissions are reduced and extra biomass becomes available in the form of residues left on the ground after the harvest, which can bring benefits such as increased soil organic matter, reduced erosion, carbon sequestration and nutrient recycling.

Sugarcane yields in new production regions in Brazil have been lower than the national average due to less fertile soil, longer periods of water deficit, and limited availability of cane varieties suited to the local conditions. The technology development in improved management practices to increase soil fertility includes adequate soil acidity correction and fertilizer use combined with pre-cropping the area with nitrogen-fixing crops such as soybeans, sun-hemp, or peanuts; and incorporating the crop residues into the soil to increase organic matter content. So-called supplementary or “salvation” irrigation to improve yields in areas with greater water deficits were adopted when necessary. New sugarcane varieties are being developed for the new production environments, and several new breeding stations were created.

In the processing plants, the main change in technology is the use of high-pressure, state-of-the-art power generation systems (boiler/turbine generator) made more economical by the expanding number of green field projects and the increase in scale. The average capacity of existing mills is 1.5 million tons of cane processed each harvesting season, only half the capacity of most of the new mills. This reduces the CAPEX and OPEX in the sugar, the cost of ethanol, and electricity generation costs, and significant increased competitiveness. Straw recovery is being tried by several mills to increase surplus power generation by the use of a supplementary biofuel from bagasse, to extend power generation into the off-season, and to improve the capacity factor of existing facilities. These are all fully mature technologies with very low risk and guaranteed cost reduction if well maintained and operated properly. Capacity building became key because the high rate of growth in sugar and ethanol production in 2007 to 2012 outpaced the ability to train the new plant operators, maintenance staff, and management staff.

In addition to producing sugar, integration of sugar cane production with food production occurs through crop cultivation (mainly soy and peanut) during renewal of the sugarcane ratoons. Some process by-products[7] are also used as animal feed. The byproducts suit a wide range of livestock production systems, but on a commercial scale, mostly apply to ruminants for beef or milk production in feedlots operating close to the mills. These feedlots were common in the 1980s and 1990s, but their numbers have declined because of the high demand for bagasse for energy cogeneration.

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[7] The most common by-products used to feed animals are hydrolyzed bagasse (steam-treated bagasse), raw bagasse, liquid yeast, dry yeast, molasses, cane straw, filter cake, vinasse, and cane tops.

6.3.2 Logistical analysis of current systems

Transport costs and the rapid loss of free sugars after harvest requires sugarcane to be sourced from areas close to the ethanol production plants. For instance, ethanol mills built in State of São Paulo before 2006 obtain basically all their sugarcane from plantations located within 40 km of the mill. The need for relatively short distances from source to mill limits the capacity to guide ethanol and associated sugarcane expansion exclusively into use-specific land types, such as extensively used pastures. In fact, payment for sugarcane is based on sugar content on arrival at the mill. In Sao Paulo, which had about 60% of the Brazilian sugarcane production in 2012, almost all of the sugarcane expansion in 2004 to 2008 took place on roughly equal shares of cropland and pasture land (Rudorff et al. 2010). An assessment of land cover and land use surrounding existing operating mills and 21 approved mill projects in the State of Sao Paulo (Figure 6.4) indicates that most new sugarcane needs to be planted on cropland unless it is sourced from longer distances than has typically been the case (Egeskog et al. 2014).

Thus, scientific studies confirm that sugarcane expansion does not cause much direct deforestation, but it is less clear whether direct competition for prime cropland is generally avoided by planting sugarcane on extensively used pasture lands. On the other hand, crops other than sugarcane can be cultivated on pastures, and the promotion of increased land productivity in meat and dairy production can consequently reduce the risk of sugarcane expansion causing indirect conversion of forests or other native vegetation land by making pasture land available for either sugarcane plantations or other crop cultivation if displaced by sugarcane.

Longer post-harvest storage times and transport distances are economically feasible for some other bioenergy feedstock alternatives such as eucalyptus, soy, and oil palm. These feedstock alternatives will benefit more from the current infrastructure expansion into northern of Brazil since they can be cultivated there. Sugarcane's climatic limitation prevents its expansion to the north, and mills are primarily located in well-consolidated agricultural areas with favorable logistics.

6.3.3 Feedstock availability at operational and whole-supply-chain scales

When bioenergy feedstocks are derived from dedicated cultivation systems, availability depends on how the feedstock cultivation interacts with cultivation for food, feed, and biomaterials. When the bioenergy sector uses the same feedstock as other sectors (e.g., sugarcane for ethanol or sugar, corn for food, feed, or biofuels) availability is a matter of: (i) payment capacity in the bioenergy sector vs other sectors; and (ii) capacity in the agriculture sector to ramp up production in response to the total growth in demand. Some crops that are suitable for cultivation on grassland and pasture are cultivated primarily for other purposes, and the bioenergy feedstock is a by-product. The availability of bioenergy feedstock is then limited by the market for the main products and by the ramp-up capacity in the agriculture sector. One example is soy, which is cultivated to produce animal feed and produces oil suitable for biodiesel production as a by-product.

As described above, many sugarcane mills in Brazil can produce both sugar and ethanol and can switch output products (within a limited range) based on price expectations. However, while the competitiveness of the ethanol system is sensitive to developments on the sugar market, the total ethanol output is not restricted by the size of the sugar market. If demand for ethanol grows more rapidly than demand for sugar, then sugarcane ethanol production can be ramped up based on constructing sugarcane mills that are dedicated to only ethanol production (and by-products such as electricity) and that can use sugarcane varieties that are optimized for ethanol production.

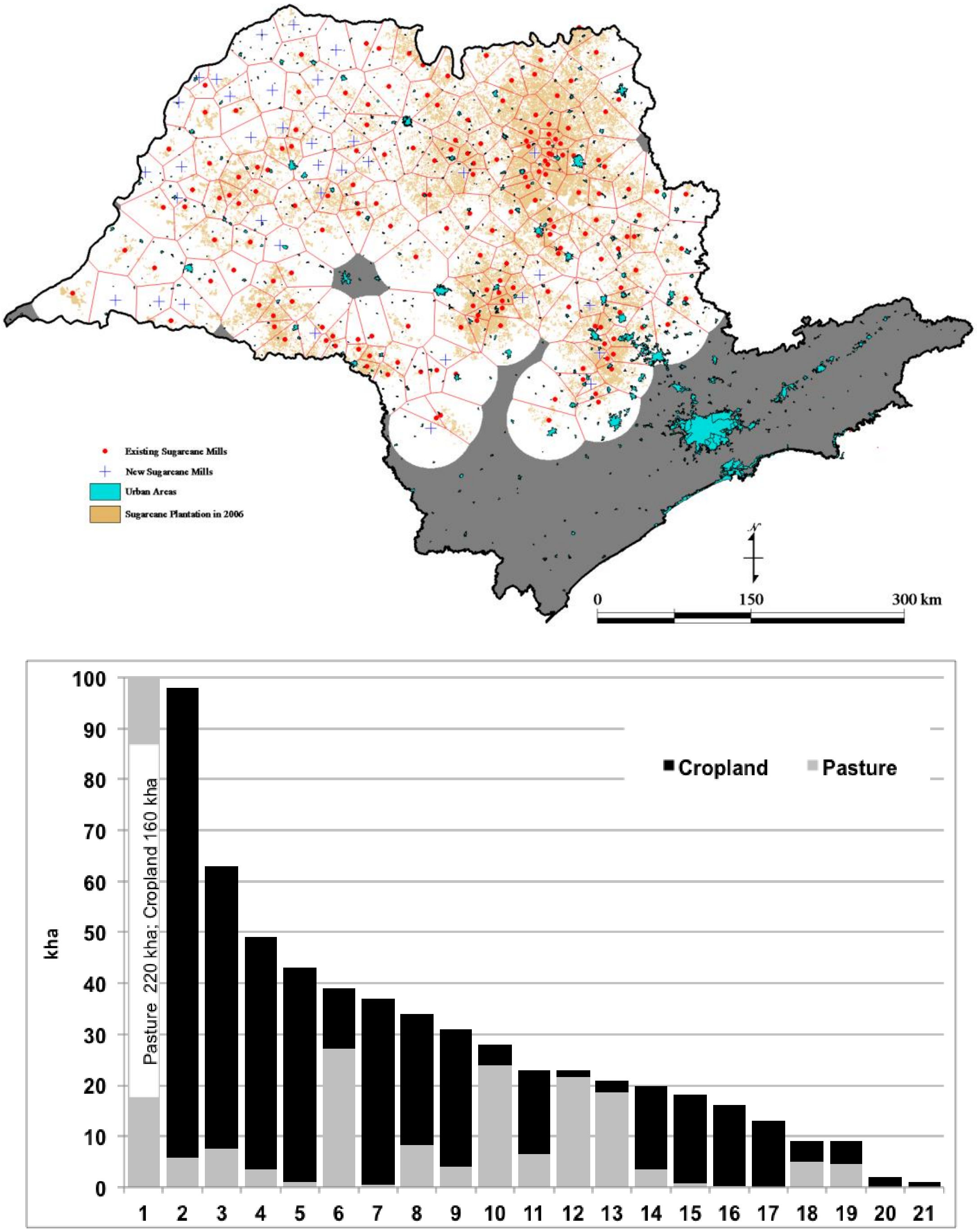

Figure 6.4. Top: Voronoi diagram relating to existing and 21 approved mills in the state of Sao Paulo. A Voronoi cell associated with a mill consists of all points closer to this particular mill than to any other mill. Some 34,000 ha of plantation land (including necessary roads) is needed to service an average size mill, assuming capacity corresponding to 2.3 Mt cane processed per season and yield at 85 t cane/ha/yr. Based on experience, Voronoi cell size was here defined by setting the maximum distance from mills to 40 km. The red dots represent locations of mills built before 2008; the + symbols represent locations of the 21 mill projects that were approved at the time of data collection. The light brown areas show where existing sugarcane plantations are located and the grey areas are either more than 40 km away from a mill or protected. Bottom: Existing pasture and cropland area within Voronoi cells surrounding the 21 mills. Each bar represents one approved mill. *Reprinted from Egeskog et al. (2014), with permission from Elsevier.*

Few techno-economic barriers exists against large scale cultivation in grasslands and pasture lands in Brazil: legal conditions for production are settled, production systems for several feedstock alternatives are mature, and there is technology and capacity to rapidly increase production in response to increasing demand. Progressive infrastructure investments further strengthen capacity, with significant investment in export routes via the Amazon river basin to support exports of soy, grain, cotton, etc. New investments aim at consolidating the North trade route by establishing new docks, barge fleets and terminals along the Amazon river and tributaries, and improving capacity of ports in, e.g., Belem, Itaituba, Santarem, Santana. Historical expansion of Brazilian sugarcane is shown in Figure 6.5, including a comparison of the most rapid expansion rates in history with expansion rates implied in our illustrative calculation in Section 6.2.2.

It can be expected that increased agriculture production will be achieved based on both land expansion and improved land productivity, with possible LUC depending on how governance systems shape development. Among the options for boosting productivity, irrigation stands out because its expansion rate is difficult to project and because it can have such a strong effect on annual outputs by facilitating multiple cropping schemes (e.g., soy with corn or cotton) on the same land area.

Some feedstock options are in development stage and will not respond as quickly to rising bioenergy demand because they are not integrated with well-established agricultural supply chains, or require specialty equipment. This includes several of the lignocellulosic grasses and short rotation woody crops that commonly are proposed as major feedstock supply systems in the longer term. However, countries

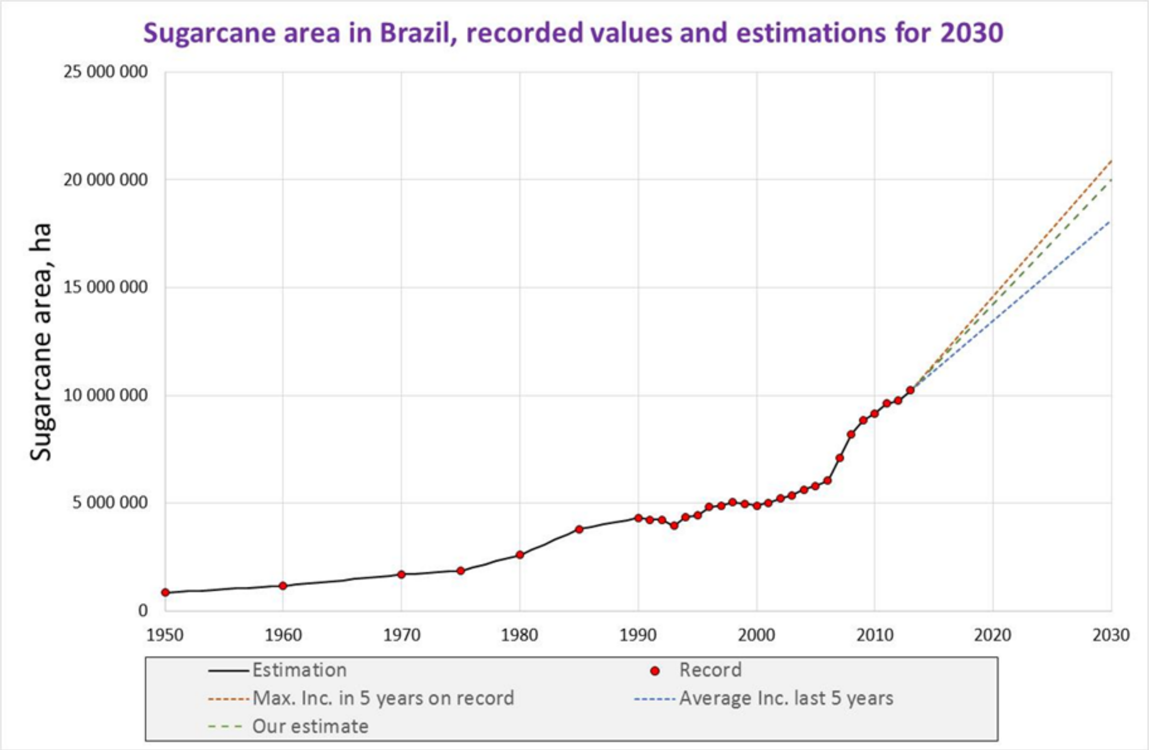

Figure 6.5. Historical expansion of sugarcane area in Brazil and a comparison of the average and maximum historical expansion rates (measured over five years) with the implied expansion rate in our illustrative calculation in Section 6.2.2.

that have extensive areas with tree plantations that provide wood for pulp and paper as well as sawn-wood products would have the capacity to ramp up production to meet growing demand for lignocellulosic biomass as bioenergy feedstock (Chum et al. 2015, Goh et al. 2013).

Feedstock availability may be restricted by policies in some markets; the decision to cap the contribution of first generation biofuels in the EU-Renewable Energy Directive (EU-RED) is one example of such restrictions. Further, barriers against mobilization may exist in the sense that markets are associated with sustainability requirements, which can limit the rate at which feedstocks become available in several ways. Depending on how sustainability requirements and governance systems are shaped to guide bioenergy growth, the rate at which feedstock availability can grow will be affected by the pace of structural shifts and incentives rewarding higher productivity in agriculture. Availability of grasslands and pastures can be a critical determinant of possible mobilization rates for feedstocks supporting the production of "low-indirect-land-use-change (low-iLUC) biofuels, because conceptual approaches for providing such biofuels often target marginal and/or "degraded" lands, which are commonly used for grazing. The large areas of grasslands and extensively used pastures in Brazil represent an important mobilization opportunity, but there are also challenges because, historically, ample supply of new land in frontier regions has fostered a culture among cattle producers and associated actors where management options to increase land-use efficiency are less important (Sparovek et al., 2015b). This is another area in which government policy can foster recovery of degraded pastures, where productivity would initially be low but then rise over time and enable both bioenergy and food crop expansion if needed.

6.4 SUSTAINABILITY ANALYSIS

6.4.1 Sustainability indicator analysis of supply chain

The sugarcane ethanol supply chain performs favourably and can improve further on critical aspects such as GHG savings and resource use efficiency. There is still significant progress to be made in power production with more efficient turbines and integrated systems. Analyses of GHG emissions and savings support the view that expansion of sugarcane ethanol in Brazil will bring about substantial GHG savings if LUC emissions are avoided (Figure 6.6). Sugarcane ethanol in Brazil also presents lower impacts than gasoline in terms of fossil fuel depletion and ozone layer depletion, but higher impacts in terms of acidification, eutrophication, and photochemical oxidation. Human health toxicity values are similar to those of gasoline (Cavalett et al. 2013). Ethanol from sugarcane refineries that use mechanical harvesting of unburned cane and configure the process to efficiently generate power qualify for the US EPA Advanced Biofuel category (meeting the 50% threshold level) and receive a 50% reduction in the EU-RED system (Figure 6.6). Caldeira-Pires et al. (2013) also stress further improvements in agricultural management to decrease fuel, fertilizer, and herbicide consumption.

Oil palm, tree plantations, and soybeans can also support bioenergy and provide GHG savings, although soybean crops are less area efficient and are a less ideal use of land above the scale defined by animal feed markets. Other environmental impacts depend on the production location. Sugarcane and oil palm cultivation on grasslands and pastures causes relatively small carbon emissions or carbon sequestration (Mello et al. 2014, Souza et al. 2015). Carbon emissions are generally larger for annual crops, although no-till production reduces soil carbon losses under annual crops. If sugarcane or oil palm displace annual crops to grasslands or pastures where their cultivation causes soil carbon losses, the fact that soil carbon simultaneously increases when the previous croplands are used for sugarcane or oil palm should also be considered. Land preparation and planting of trees can induce soil carbon losses, which are balanced by subsequent soil carbon gains depending on plantation management (Smith et al. 2014).

As described throughout this chapter, the opportunity to cultivate grasslands and pastures cannot be investigated based on analyzing bioenergy options in isolation from other land uses, because cultivation of grasslands and pastures is attractive also to producers of other crops. This also means that availability of grasslands and pastures can accommodate expansion of cultivation systems that become displaced if bioenergy feedstock production expand on croplands. Thus, LUC, with its associated impacts, is not a concern for the bioenergy sector alone: a key question for Brazilian production of food, biofuels, and bioproducts is how the growing agriculture production affects the environment as well as social and economic development. The overall impacts need to be analysed together for the specific landscape, watershed, and biomass types for all their uses, and considering spatial and temporal dimensions (e.g., multiple cropping). While information is lacking concerning bioenergy feedstock expansion on grasslands and pastures globally, it has been shown by Souza et al. (2015) that the net cropland area claimed for biofuels is so far relatively small; an analysis of the 34 largest biofuel producing countries, which accounted for over 90% of global biofuel production in 2010 indicates that the increase in biofuel production from 2000 to 2010 resulted in a gross land demand of 25 Mha out of a total of 471 Mha arable land. However, nearly half the gross biofuel land area was associated with commercial co-products (primarily animal feeds), leaving a net direct biofuel land demand of 13.5 Mha, or 2.4% of arable land area. Despite this increased land demand for biofuel feedstock production, total agricultural land area decreased by 9 Mha in the evaluated countries as a result of increasing cropping intensity. See also Langeveld et al. (2013).

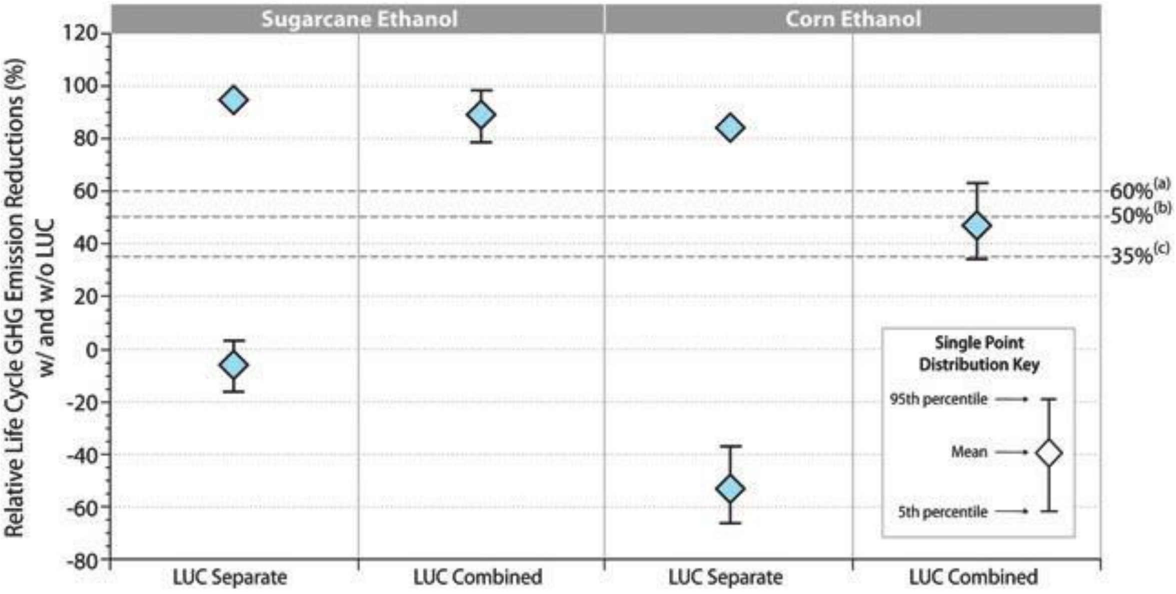

Figure 6.6. Relative life cycle GHG emissions reductions for Brazilian sugarcane ethanol and USA corn ethanol, with and without LUC-induced GHG emissions separated from supply-chain GHG emissions. The highest points in the "LUC separate" fields correspond to the relative GHG reductions when excluding LUC and considering only the well-to-tank life cycle GHG emissions. The lowest points in the "LUC separate" fields (that include uncertainty ranges) correspond to the Monte Carlo distributions of LUC emissions. These LUC emissions are combined with well-to-tank life cycle GHG emissions to obtain the relative reduction when including LUC, shown in "LUC combined" fields. Legislated reduction: (a) 60% US EPA-classified cellulosic biofuel; (b) 50% US EPA-classified advanced biofuel; (c) EU-RED (Chum et al. 2014).

If land productivity growth continues to outpace growth in demand, so that the increase in production volume is decoupled from area expansion, environmental impacts will, to a greater degree, arise because of the agricultural management used to achieve the intensification, i.e., nutrient and pesticide leaching, soil erosion, etc. Implementation of best management practices will consequently be crucial for mitigation of environmental impacts. In Brazil, best management practices for cultivating low productivity pastures will be especially important since much of the land that can become available through intensification is currently used for extensive grazing.

Irrigation, currently occurring on 6 out of nearly 70 Mha of cropland, could expand the agricultural frontier by adding areas unsuitable for rain-fed agriculture but suitable for cropping under irrigation. About 27 Mha of such land is located in areas where no important competition for water is foreseen, and no additional conversion of natural systems is needed to support the irrigation expansion. Most of these areas are also located in poor regions, neighboring the main important areas of agricultural production in the Center and South of Brazil and in the recently consolidated region of crop production called "MAPITOBA" located in transitional areas between Cerrado and Caatinga biomes (FEALQ/IICA/MI, 2015). Since these areas are coincident to regions with significant amounts of unprotected native vegetation, governance systems balancing nature conservation and agricultural production will be important.

Some marginal lands (including grasslands) support relatively high levels of biodiversity and widespread use of marginal lands might therefore impact biodiversity (Chum et al. 2011). WBGU (2009) indicates that biodiversity considerations can have a larger impact on technical biomass potential than either irrigation or climate change; however, more current studies indicate that available land resources exceed the projected needs for biodiversity conservation in terms of the Convention on Biological Diversity’s target for protected area systems to expand to 17% of the global terrestrial area (Joly et al. 2015). It has also been shown that to some extent crops grown on degraded or abandoned land such as degraded cropland and grassland could have positive impacts on biodiversity by restoring or conserving soils, habitats, and ecosystem functions (Firbank 2008, Danielsen et al. 2009, Joly et al. 2015).

As for food and feed crop production, bioenergy feedstock production can occur in monoculture systems that use large amounts of synthetic fertilizers, pesticides and other inputs. Such systems are often criticized due to impacts on the environment, public health and rural communities. More holistic approaches to land use have been called for that can better address issues associated with the complexity of food and other production systems in different ecologies, locations and cultures (see, e.g., IAASTD 2008). I should be noted that there are many ecosystems where monocultures develop naturally in forest and grassland biomes at both stand and landscape scales. The sustainability criterion of interest is most appropriately monitored at landscape to regional scales since the full range of micro- and meso-habitats will be sampled and inform the analysis. Nevertheless, the promotion of holistic approaches and a stronger link between agriculture and ecology is essential since a narrow focus on biomass production can reduce the value of biomass plantings with regard to the provision of other ecosystem services (see also Chapter 5).

6.4.2 Governance

6.4.2.1 Brazil

Figure 6.7 illustrates the current land governance structure in Brazil, including areas under several types of ownership and regulation. The trend in Brazilian agriculture is toward greater legal compliance and standardization. The approval in 2012 and current implementation of the revised Forest Act

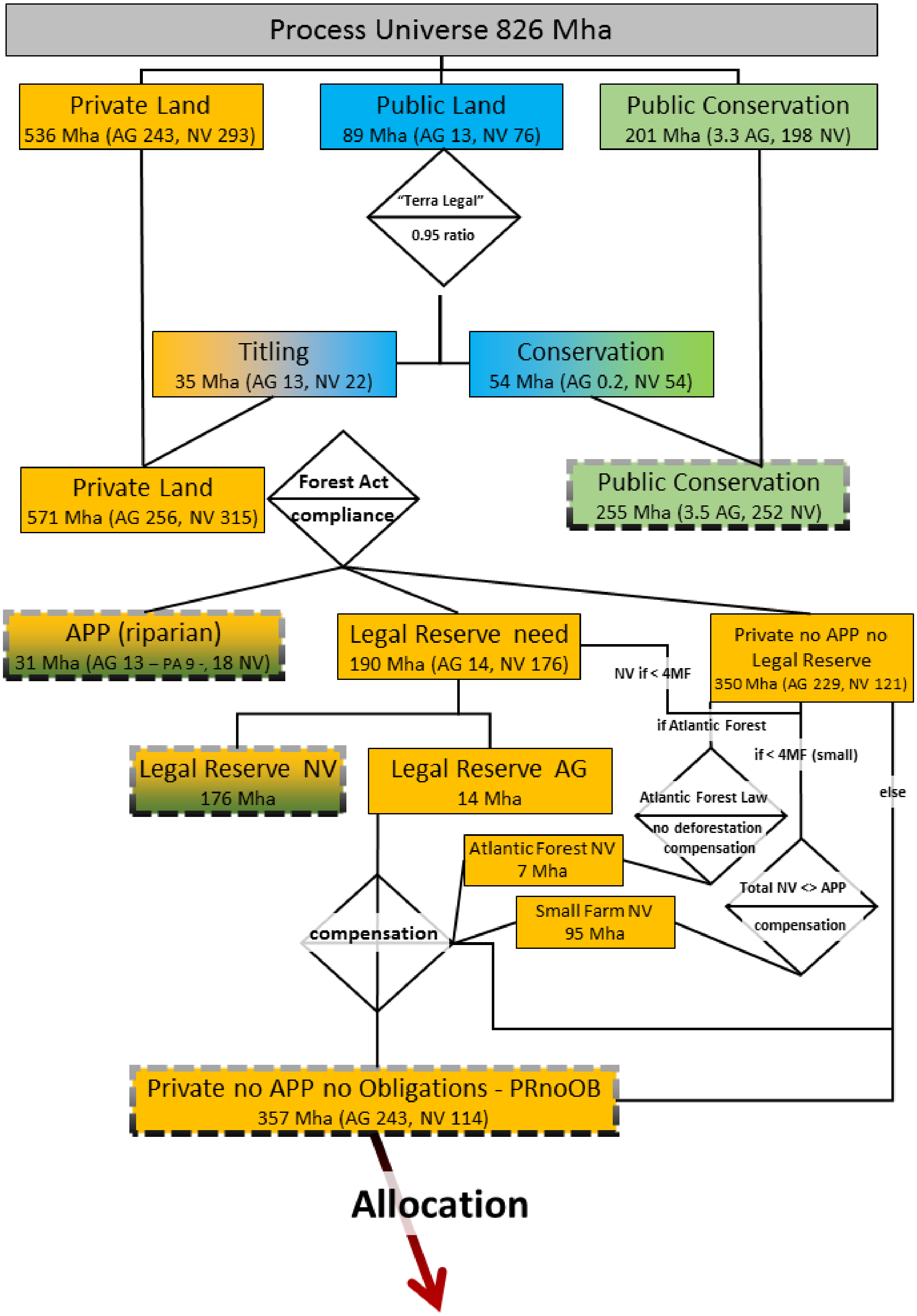

Figure 6.7. *Land governance structure in Brazil; area of land under different types of ownership and regulation and legally available for agriculture. National area totals. The Figure also shows the land allocation principles used in the assessment presented in Section 6.2.2. NV: native vegetation; APP: areas under permanent protection; AG: agricultural land. Reprinted with permission from Sparovek et al. (2015a). Copyright 2005 American Chemical Society*.

changed the rules to facilitate legal compliance by reducing the requirements for land set-asides and/or restoration of native vegetation on productively used farmland. The revised Forest Act also includes a comprehensive environmental rural registry that facilitates monitoring and surveillance by government and civil society.

Amazonian deforestation rates have drastically declined since 2004 and the deforestation rate in 2014 was roughly 75% below the average for 1996 to 2005. Explanatory factors include effective surveillance and articulated networking of civil society and governmental agencies, as well as actions among important stakeholders in the agriculture sector (e.g., the soy moratoria) recognizing that businesses are negatively impacted by association with environmental degradation, especially in the Amazon (Nepstad et al. 2014). Analyses indicate that the focus on command and control measures on larger properties in deforestation hotspots may be increasingly limited in their effectiveness, and that further reductions in deforestation are likely to require actor-tailored approaches, including better monitoring to detect small-scale deforestation and more incentives-based conservation policies (Godar et al. 2014).

Consumer demand for certified agricultural products is increasing and an increasing share of Brazilian agriculture is adopting certification schemes. Governmental land entitlement initiatives reduce the degree of informality and legal noncompliance in the land use sector. Global corporations are increasing their share in agricultural businesses, and these corporations are more sensitive to public image issues than individual farmers are, and less permissive with respect to legal nonconformity. Stakeholders' commitments have also grown more ambitious. These trends towards increased compliance and adoption of voluntary control standards reflect underlying and long-term external and endogenous drivers.

Governance of land use in Brazil is complicated by the fact that opposing sides in stakeholder disputes have ignored progress in balancing agricultural production and nature conservation, especially related to expansion in frontier regions (Sparovek et al. 2015b). The common ground perspective that agricultural and conservation interests can be compatible is challenged by old and deeply rooted mutually *exclusive* conceptions and positions of opposing sides. Mutually exclusive agendas may be favored over compatible agendas if they are strategically and tactically advantageous in processes shaping the governance of land use in Brazil. The polarizing positions expressed during the Forest Act discussions, and repeated on other occasions, indicate that stakeholders have indeed judged that debate and conflict will bring the most beneficial outcome. As a consequence, much of public opinion — and in turn government decision making concerning Brazilian agriculture and conservation — appear to be shaped by a perceived conflict between these objectives and a debate that has become, at least to some extent, an end in itself.

6.4.2.2 Global

Assessment and certification schemes differ in degree of protection of environmental values and economic, social, and other implementation criteria. Diverging views on sustainability aspects and indicators around the world may reduce the effectiveness of sustainability certification systems, many voluntary, intended to support mobilization of sustainable bioenergy supply chains — sustainability being defined according to the particular principles and indicators chosen for evaluating the supply chain (Stupak et al. 2015). Thus, while biofuel producers and global trade companies create pressure towards legal regulation and engagement in certified production among feedstock producers, leakage effects may reduce the effectiveness of governance mechanisms.

Conversion of grasslands and pastures to bioenergy plantations will be affected in various ways by policies and regulations intended to protect biodiversity. One example of such regulation is found in the

EU-RED where it is stated that biofuels and bioliquids shall not be made from raw material from "... land with high biodiversity value, e.g., areas designated for nature protection purposes, primary forest and highly biodiverse grassland" (European Parliament and Council 2009). Within the EU there has been a process to define the criteria and geographic ranges of highly biodiverse grassland (see e.g., European Commission 2014), and this process might continue in the future for solid biomass as well.

Schueler et al. (2013) estimated that 90% of a theoretical global and regional biomass potential is affected by the EU-RED sustainability criteria. They also indicate that about 60% of this biomass supply potential is subject to biodiversity considerations. Böttcher et al. (2013) report that about 8% and 5% of global grassland and natural vegetation, respectively, are considered to be highly biodiverse.

Until now, few studies allow for quantification of how consideration of highly biodiverse grassland influences the biomass mobilization potential. Besides data and methods to distinguish highly biodiverse grassland from other land, there is a need for studies of the supply potential of biodiverse grassland that require management with biomass extraction to maintain its biodiversity status. Uncertainties will be reduced as schemes for demonstrating compliance with biodiversity requirements contribute to the establishment of criteria and geographic ranges of highly biodiverse grasslands.

6.5 SYNTHESIS

6.5.1 Constraints and barriers

There remain few techno-economic barriers against mobilization of bioenergy supply chains in Brazil: legal conditions for production are settled throughout the country, production systems are mature, and there is technology and capacity to rapidly increase production in response to increasing demand. Progressive infrastructure investments further strengthen capacity. Large GHG savings can be achieved if large LUC emissions are avoided.

Brazilian agricultural production can grow without extensive conversion of forests and other native vegetation. Large areas of extensively used pastures are suitable for cultivation of sugarcane and other bioenergy feedstocks, and land productivity improvements in meat and dairy production can accommodate an expansion of such cultivation. Irrigation can boost agriculture production in Brazil and in many other countries around the world.

However, bioenergy mobilization is hampered by uncertainty concerning future markets and evolving regulations. Specifically for the sugarcane system, low margins for sugar and ethanol are magnifying the importance of surplus electricity sales to the grid but several barriers inhibit development for electricity co-generation in ethanol mills. Furthermore, the recent revision of the Brazilian Forest Act resulted in less protection of native vegetation, and less stringent requirements for restoration planting and assisted regeneration of natural ecosystems on agricultural land. Large areas with native vegetation can legally be converted to agriculture use and ample supply of land reduces the interest in management options to increase land-use efficiency.

Consumer demand for sustainable agricultural products is increasing, but sourcing is challenging due to the variety of issues to be considered and the many suggested indicators for representing these issues. Diverging views on sustainability aspects and indicators around the world may result in leakage effects that reduce the effectiveness of sustainability certification systems — sustainability being defined according to the particular principles and indicators chosen for evaluating the supply chain. Biodiversity and hydrological aspects of grassland and pasture cultivation need further attention.

Finally, the polarized debate about the Brazilian agriculture development and environmental protection may in itself be a barrier against progress, since debate and conflict contributes to uncertainty about future markets, including sustainability standards and regulations imposed on producers.

6.5.2 Supporting the mobilization of sustainable bioenergy supply chains

The last decade has seen significant improvements in the productivity and efficiency of Brazilian agriculture, great reductions in deforestation rates, and growth in environmentally certified production. Science-based information supports the view that agricultural and conservation interests can be met simultaneously, because there is sufficient area to meet both conservation and production objectives. Improving productivity is perceived to be important by the agricultural sectors in Brazil and by those that prioritize environmental values. From this perspective, the current trends and achievements are promising.

Further mobilization of sustainable bioenergy supply chains can be supported by:

- Clear and consistent policy definitions and targets providing stable market conditions. Policies can either guarantee markets or increase fossil fuels prices sufficiently to make ethanol and other bioenergy options competitive. More favourable conditions for power generators and resource planning integrating biopower with other power resources can stimulate development especially in newer sugarcane mills where increasing scale improves conditions for electricity cogeneration.
- Good governance that balances agriculture production and conservation objectives to provide biomass and bioenergy products that meet sustainability requirements. This requires both incentives and alternative regulation (e.g., licences and conditional credits) that complement governmental command and control to protect native vegetation and promote higher land use productivity in the agriculture sector.
- Improved productivity in meat and dairy production and best management practices for cultivating low productivity pastures will be especially important, since much of the land that can become available through intensification is currently used for extensive grazing.
- Criteria, data and methods are needed to distinguish highly biodiverse grassland from other land and to address hydrological aspects of grassland and pasture cultivation.
- Actor-tailored approaches may be needed to achieve further protection of native vegetation, including better monitoring to detect small-scale deforestation and more incentives-based conservation policies.

A common-ground agenda, balancing conservation and agricultural development objectives, may be difficult to establish as long as conflict and dispute is considered desirable by many stakeholders involved with — or affected by — governance of Brazilian land use and biomass production. However, a structured exchange involving nine experts associated with major producer interests (livestock, crops, planted forest, and charcoal) and environmental NGOs (Sparovek et al. 2015b) revealed agreement that the majority of actions and expected future trends in Brazil reflect achievements and ambitions to balance production and conservation objectives. (See Figure 6.8.) Decision-support systems that integrate relevant biophysical and socio-economic data were developed and used in this project, and these decision-support systems are now used to guide mobilization of sustainable production systems for food, bioenergy, and biomaterials at several Brazilian ministries (i.e., Ministry of Integration, Ministry of Agriculture, and Ministry of Agrarian Development).

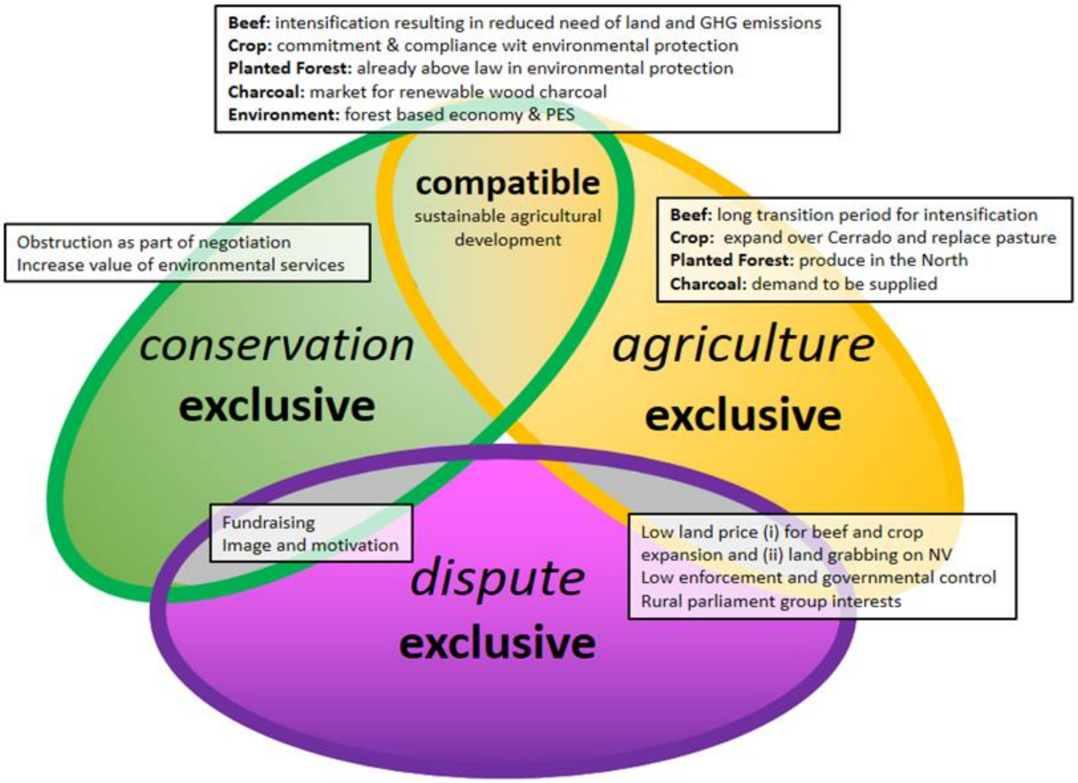

Figure 6.8. Core issues and viewpoints of nine experts associated with major producer interests (livestock, crops, planted forest, and charcoal) and environmental NGOs.

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7

INTEGRATION, SYNTHESIS, CONCLUSIONS, AND RECOMMENDATIONS

7.1 INTRODUCTION

This report and the wider body of work which it synthesizes use a case study approach to explore the role that bioenergy might play in meeting renewable energy goals and reducing global carbon emissions. Regional case studies of specific bioenergy supply chains provide a level of detail that helps to more accurately answer wider questions such as the following:

- How much biomass could be sustainably and economically harvested for bioenergy purposes now and over the next 50 years?
- How do regional differences (e.g., physical, political, social, economic) affect biomass availability and supply chain development?
- Are various supply chains sustainable, and how can sustainability concerns be addressed?
- What barriers exist to the mobilization of sustainable bioenergy supply chains?
- What opportunities exist to encourage the mobilization of sustainable supply chains, and how might they be realized?

This chapter briefly synthesizes the rich detail provided by the case study analyses, extracting the main take-home messages that appeared again and again across case studies, and generalizing these findings to broader applicability, as appropriate.

7.2 BIOMASS AVAILABILITY

A wide variability in estimates of biomass potential for each of the supply chains and regions studied was evident throughout the case study analysis. Arriving at accurate and precise estimates is challenging, because biomass availability depends on a diverse set of dynamic factors such as

- policy incentives and barriers;
- availability of land (where purpose-grown crops are concerned) and competing land uses;
- competing uses for residues (e.g., forest residues, crop residues) and primary products (e.g., small diameter trees, lignocellulosic crops);
- market demand;
- sustainability requirements;
- operational efficiencies and supply chain optimization;
- costs of competing energy sources;
- location and physical accessibility of biomass; and
- impacts from weather events (short term) and climate change (longer term).

Published estimates must be based on sets of assumptions made by authors and modellers, which accounts for their wide range of variation.

Common across most of the case studies were the following take-home messages:

- Promises based on unrealistic estimates of availability, costs, and timetables can make decision makers wary of promoting and investing in bioenergy; therefore working towards realistic goals is important to maintaining stakeholder interest in bioenergy and encouraging supply chain mobilization.
- Understanding the assumptions underpinning the wide range of available estimates is critical to evaluating them and choosing those likely to be most accurate in any given context.
- It is perhaps most useful to consider estimates as a range of possibilities based on different scenarios that take into account some of the dynamic factors listed above.
- The most accurate estimates account for regional variations and operations-level considerations.

Each supply chain has its own unique constraints that will limit feedstock supply and dictate the size and scale of sustainable operations (locally, regionally, and globally); however, there are also numerous barriers, both generally relevant and specific to particular supply chains, that must be overcome to significantly increase the amount of feedstock available for sustainable bioenergy production.

7.3 DRIVERS FOR BIOENERGY MOBILIZATION

The most prominent driving forces for modern bioenergy expansion on a global scale are political instruments, agreements, and regulations to reduce reliance on non-renewable, imported fuels and to meet GHG-reduction targets. The growth of the bioenergy sector is also driven by other factors including rural economic development and employment; a need for product diversification in the forest and agricultural sectors; the desire to find innovative uses for residue streams and waste products; and even efforts to improve the productivity of forests, fields, and degraded lands.

7.4 ECONOMIC COMPETITIVENESS OF BIOENERGY SUPPLY CHAINS

Generally speaking, policy drivers aimed at renewable energy production and domestic energy security have been more critical in influencing bioenergy expansion than market factors, and as a result many supply chains are not yet economically viable without external support beyond local, small-scale applications (with the exception of more mature, proven supply chains such as sugar cane ethanol in Brazil, certain waste-to-energy systems, and biomass-based combined heat and power in regions such as Denmark). Government support and financial incentives therefore continue to be important to encouraging the mobilization of bioenergy supply chains.

Whether or not supply chains achieve economic self-reliance over time depends on a number of factors, including the relative costs of competing energy sources, technology development, improvements in transportation efficiencies, competing land uses and land costs, labour costs, and supply chain optimization.

While some of these factors are resistant to change, continued research and development into supply chain optimization and the improvement of technologies across the supply chain (i.e., harvesting, processing and combustion) are essential for reducing costs and increasing the economic competitiveness of bioenergy operations. (See more on this under "Opportunities.")

7.5 SUPPLY CHAIN SUSTAINABILITY

If bioenergy supply chains are to be sustainable over the long term and appeal to a wide range of stakeholders, they must be economically attractive, be socially acceptable and/or offer social benefits to communities, and maintain or improve ecosystem services.

In situations where trade-offs among values are necessary, stakeholders will need to evaluate and agree on which values are most important in a given context, which trade-offs are considered acceptable, and how systems can be designed to minimize negative consequences while maximizing desired benefits.

7.5.1 Social and economic sustainability

Bioenergy supply chains tend to have a number of positive economic ripple effects at the community level. They can boost local employment, add value to existing forest and agricultural production systems, and decrease the need for imported fuels. Therefore, at a macro level, bioenergy supply chains tend to fare well from an economic standpoint through the benefits that they bring.

At a micro-level (i.e., the economic viability of businesses along the supply chain), economic sustainability varies from case to case. Emerging supply chains are less likely to have achieved economic self-reliance than more mature, proven supply chains. The social sustainability of bioenergy supply chains depends on feedstock source and competing uses (e.g., the issue of food vs fuel), security of land tenure, and human and labour rights in the regions where feedstock production takes place. Worker safety, land use conflict, and food insecurity are some of the potential negative social effects that can be associated with biomass production and bioenergy use. Job creation, energy self-sufficiency, and rural uplift are some of the potential social benefits. In Europe and North America especially social impacts tend to be positive, while in nations with corrupt governments and without effective legislation negative impacts can occur.

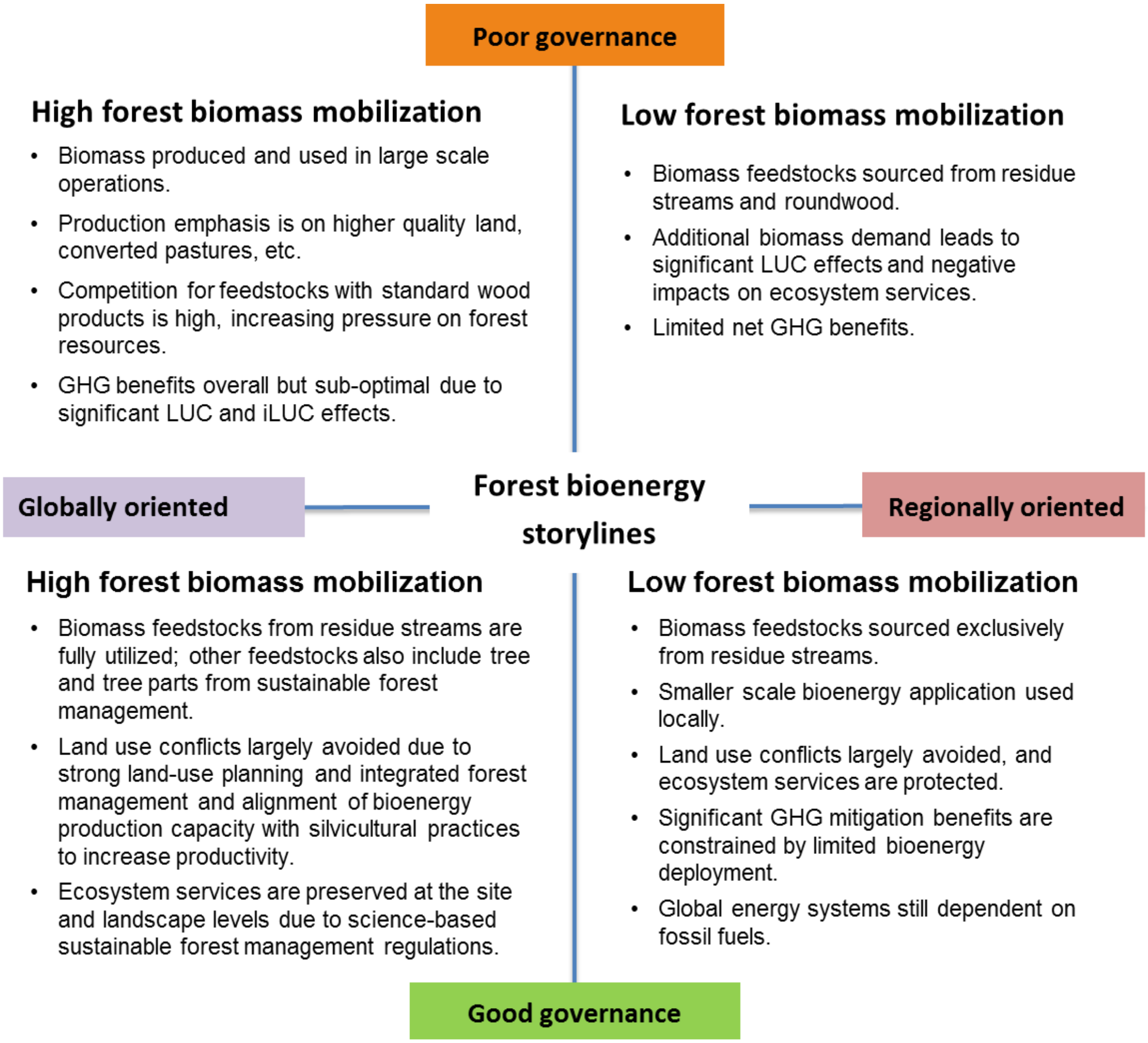
7.5.2 Environmental sustainability

Biomass production and harvesting can have a number of positive environmental impacts, such as reducing GHG emissions through the replacement of fossil fuels, increasing biodiversity and reducing erosion (e.g., where certain lignocellulosic crops replace annual crops or are planted on non-diverse degraded lands), and reducing wildfire risk (e.g., through silvicultural thinning operations). Increased biomass mobilization can also pose a number of potential risks to biodiversity, soil fertility and productivity, and water quality and quantity, if not carried out in a sustainable manner.

It is therefore critical to identify site-specific risks and address them through the use of science-based criteria and indicators, guidelines, and best management practices, using an adaptive management framework to ensure that practices continue to evolve and adapt as the knowledge base grows (see Lattimore et al.).

The sustainability of bioenergy supply chains will depend on the nature and scale of the supply chain, regional and site-specific factors (physical, social, political), and the effectiveness of systems.

Sustainable supply chain mobilization at various scales can be possible in the presence of effective guidance and good governance, leading to GHG mitigations and other positive impacts described in this report. Alternatively, where governance is weak or absent detrimental impacts can occur from increased bioenergy deployment, and the extent of these impacts will depend on the scale and geographical reach of operations. Figure 7.1 outlines a number of potential future scenarios for bioenergy sustainability based on the presence or absence of good governance and the degree of globalisation inherent in operations.



Poor governance

High forest biomass mobilization

- Biomass produced and used in large scale operations.
- Production emphasis is on higher quality land, converted pastures, etc.
- Competition for feedstocks with standard wood products is high, increasing pressure on forest resources.
- GHG benefits overall but sub-optimal due to significant LUC and iLUC effects.

Low forest biomass mobilization

- Biomass feedstocks sourced from residue streams and roundwood.
- Additional biomass demand leads to significant LUC effects and negative impacts on ecosystem services.
- Limited net GHG benefits.

Globally oriented

Forest bioenergy storylines

Regionally oriented

High forest biomass mobilization

- Biomass feedstocks from residue streams are fully utilized; other feedstocks also include tree and tree parts from sustainable forest management.
- Land use conflicts largely avoided due to strong land-use planning and integrated forest management and alignment of bioenergy production capacity with silvicultural practices to increase productivity.
- Ecosystem services are preserved at the site and landscape levels due to science-based sustainable forest management regulations.

Low forest biomass mobilization

- Biomass feedstocks sourced exclusively from residue streams.
- Smaller scale bioenergy application used locally.
- Land use conflicts largely avoided, and ecosystem services are protected.
- Significant GHG mitigation benefits are constrained by limited bioenergy deployment.
- Global energy systems still dependent on fossil fuels.

Good governance

Figure 7.1. Possible bioenergy scenarios based on scale of biomass utilization and presence or absence of good governance (adapted from Chum et al. 2011).

7.6 BARRIERS TO SUPPLY CHAIN MOBILIZATION

The mobilization of sustainable bioenergy supply chains is currently challenged and constrained by a number of institutional, technical, financial, and social barriers, summarized in Figure 7.2.

7.6.1 Institutional barriers

Ironically, while political goals, instruments, and regulations are major driving forces for bioenergy they can also act as significant barriers to mobilization. Uncoordinated and often contradictory policies regarding energy, forestry, agriculture, and climate change can dramatically slow down sustainable bioenergy mobilization and run counter to fulfilling renewable energy and GHG-mitigation goals.

7.6.2 Technical barriers

The availability of biomass and the efficiency of supply chains are both strongly dependent on operational conditions, including local ecological, social, economic, and institutional factors. Supply chains operating in regions with abundant and physically accessible land and/or resources, access to efficient technologies, established sustainable harvesting regimes, coordinated policies, high levels of stakeholder cooperation, and ongoing research and development face the fewest technical barriers to biomass mobilization (e.g., forest biomass in Scandinavia, sugarcane in Brazil). Conversely, biomass availability and supply chain mobilization will be limited by

- inefficient technologies,
- unsustainable harvesting practices,
- low levels of supply chain integration,
- shortages of skilled labor,
- lack of experience, and
- competing interests.

7.6.3 Social and economic barriers

The mobilization of bioenergy supply chains is often constrained by high up-front costs, limited financing options, and high levels of uncertainty regarding long-term feedstock availability and economic profitability. Uneven distribution of costs and benefits along the supply chain can also be an issue. Risk aversion is highest where examples of successful operations are lacking, e.g., where functioning demonstration plants, small-scale niche operations, or larger commercial plants are absent. Supply chains still in their infancy may also be constrained by a lack of supporting infrastructure, which in turn is limited by a lack of market demand. This represents a chicken-and-egg problem that can be difficult to overcome without government investment or other non-market incentives.

Public perception can form another social barrier to supply chain mobilization. Lobby groups that present bioenergy as an unsustainable energy choice can influence the general public, creating a hostile environment for bioenergy. The presence of effective, science-based, sustainability requirements, good governance systems, and public education campaigns may help to overcome this barrier.

7.7 OPPORTUNITIES

The list of barriers to mobilizing sustainable bioenergy supply chains may appear daunting, but fortunately there is an equally long list of corresponding opportunities. The case studies in this report have presented solutions for overcoming barriers to the mobilization of sustainable bioenergy supply chains, and also opportunities for enhancing environmental, social, and economic values through sustainable supply chain development (see Figure 7.3.).

7.7.1 Solutions for supporting the mobilization of sustainable bioenergy supply chains

Critical to supporting the mobilization of sustainable bioenergy supply chains is **continued research and development in supply chain optimization**, particularly developing cleaner, more efficient, and more cost-effective technologies. For example, it is estimated that an overall cost reduction potential of up to 25% is possible from better technology, improved harvesting, and optimized long-distance transport in the case of forest bioenergy supply chains (e.g., improvements in harvest machinery and combustion technologies, advances in feedstock densification, and use of “depots” to convert residues into intermediate forms more suitable for long-distance transport and storage) (Hogan et al. 2010). Expanded funding for research programs and demonstration plants would support necessary technological innovation and supply chain optimization.

Significant opportunities also exist to increase supply chain efficiencies through **technology transfer** (from regions with well-developed supply chains to regions with minimal bioenergy deployment) and **learning-through-doing.** Technical learning and putting entrepreneurs to work to increase profits and reduce costs is critical to advancing the efficiency and economic competitiveness of bioenergy systems. Transferring best practices and technologies from more experienced regions while accounting for regional differences, optimizing local conditions, and making use of existing infrastructure can be effective in getting supply chains off the ground.

Streamlining biomass supply chains with existing silvicultural and agricultural practices (e.g., timing of operations, use of machinery) is another opportunity to increase efficiencies and cost effectiveness, while at the same time increasing the overall productivity of existing practices.

Using small-scale, niche applications as a platform for scaling up may be another effective approach to testing and improving supply chain technologies, gaining experience and increasing stakeholder and investor confidence. **Improved financing opportunities for bioenergy** would make entry into the market more attainable for smaller firms and enable the development of scalable enterprises such as these.

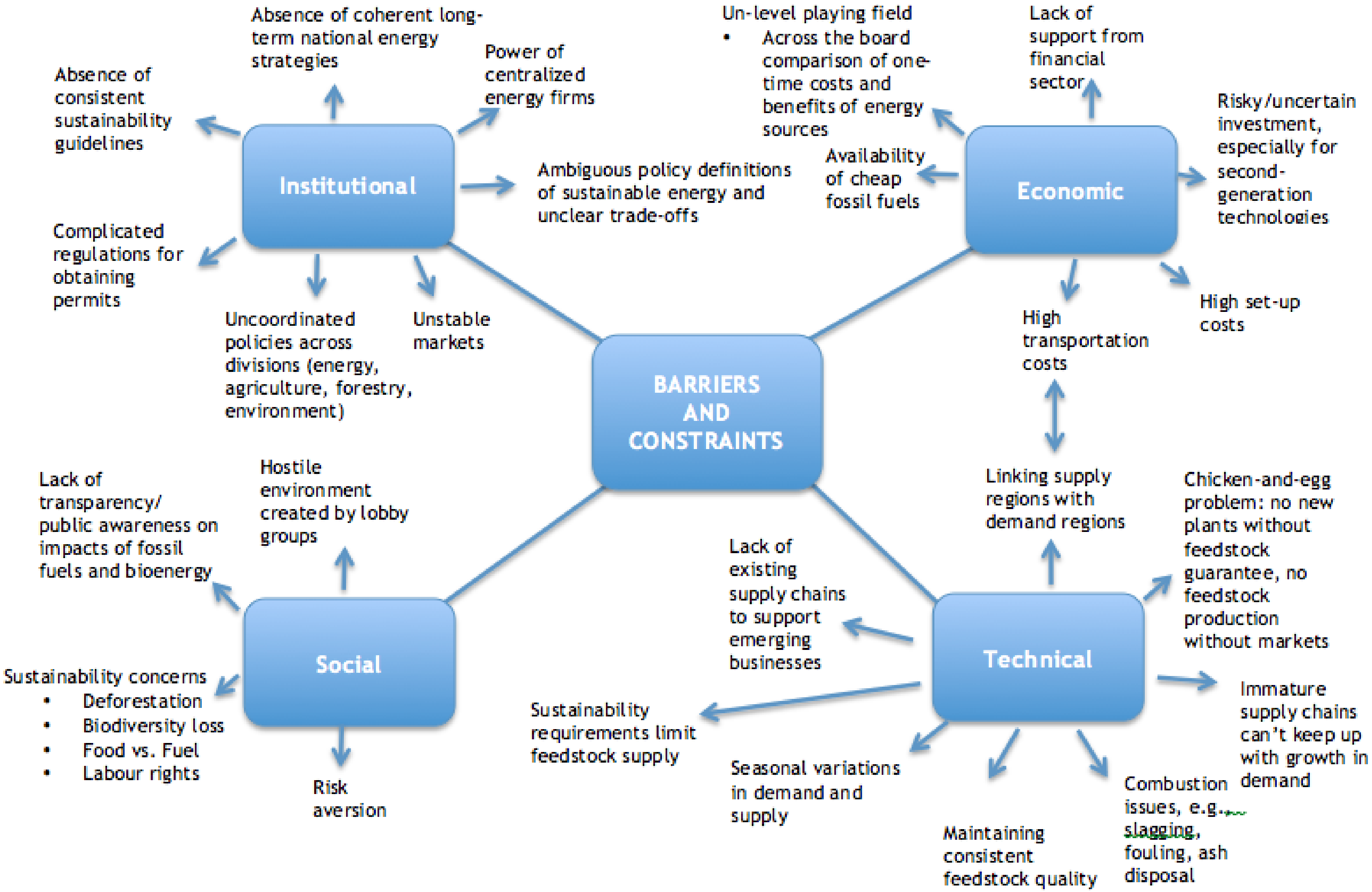


Figure 7.2. Constraints on biomass supply and barriers to sustainable bioenergy supply chain mobilization

From an institutional standpoint there are a number of opportunities to not only create a more conducive environment for the mobilization of sustainable bioenergy supply chains but at the same time also improve management for other renewable resources. These include:

- the development of **internationally accepted sustainability standards** for biomass;
- the creation **of incentives to improve the management of renewable resources in general** (e.g., biomass sustainability standards may lead to a demand for similar standards for other resources and/or may address management issues that have previously been overlooked);
- the **development of a common agenda for agriculture and forestry** that balances demands for traditional products (e.g., food, wood products, fiber), biomass and ecosystem services;
- the **creation of cooperative organizational structures along the supply chain** (biomass suppliers, energy firms and trade centers);
- increased **incentives and regulatory control encouraging better management for land productivity** (e.g., as discussed in Chapter 6, to allow for the production of multiple products without putting additional strain on ecosystem services);
- the **use of decision support systems** integrating biophysical and socio-economic data to guide the sustainable mobilization of biomass, food, and other resources;
- the **coordination of energy, forestry, agriculture and climate change policies** at national and multi-national levels;
- the **creation of common, clear and consistent definitions** related to renewable energy and climate change;
- the provision **of long-term guaranteed financial support (e.g., feed-in tariffs, subsidies, renewable energy credits, etc.)** for emerging businesses; and
- **government support for research and development programs**.

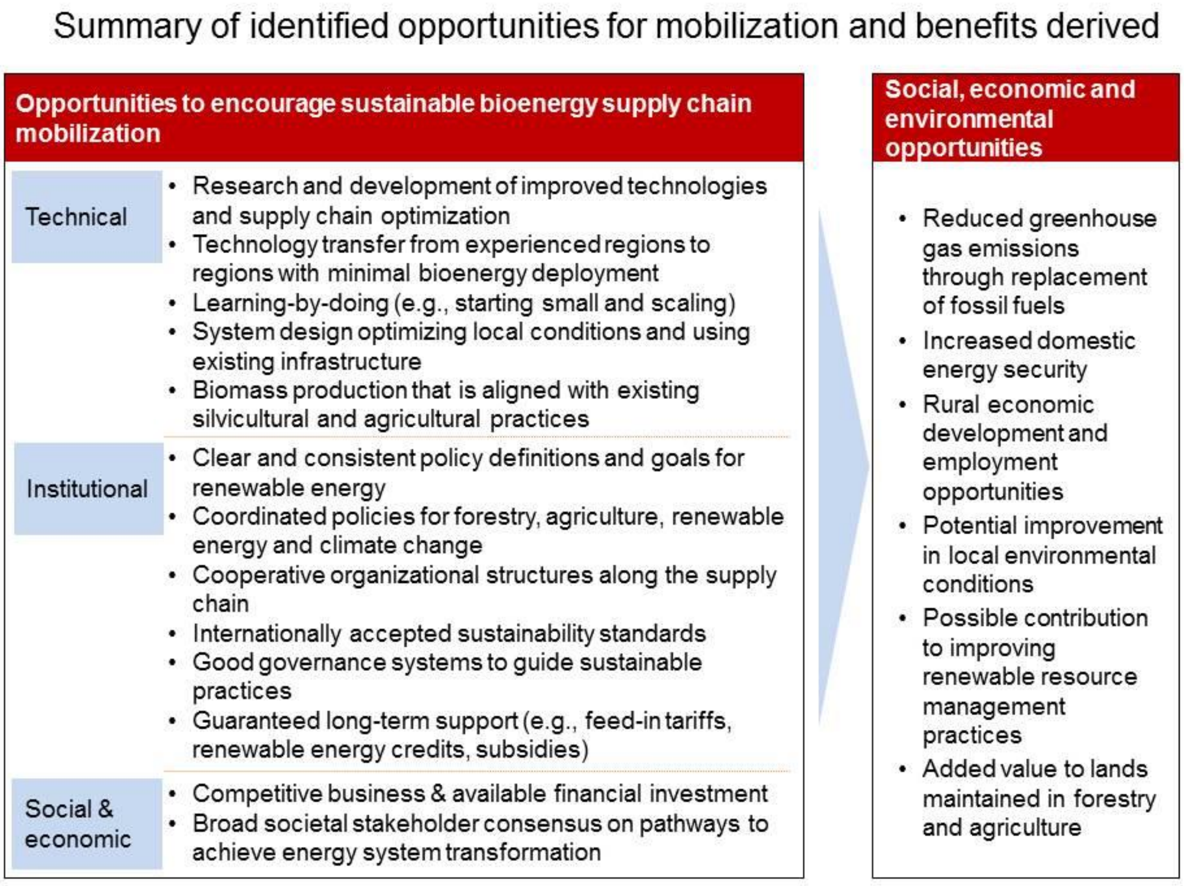
7.7.2 Potential environmental, social, and economic benefits of sustainable bioenergy production

With careful planning and management, sustainable bioenergy supply chains can provide a number of opportunities to improve on social, economic, and environmental values. These include:

- reducing greenhouse gas emissions through the replacement of fossil fuels;
- increasing domestic energy security;
- adding value to existing silvicultural and agricultural practices;
- boosting rural economies;
- creating job opportunities;
- improving biodiversity, soil productivity and/or hydrological conditions (e.g., where carefully designed lignocellulosic crops replace or complement annual cropping systems; better waste

management opportunities through biogas production; adding value to lands kept in forests or agriculture; etc.);

- encouraging dialogue on sustainable land use management for multiple products, including the development of sustainability criteria and indicators and efforts to assess the efficacy of governance systems for renewable resource management; and
- inspiring technological innovation in forestry, agriculture, and waste management.



Summary of identified opportunities for mobilization and benefits derived

Opportunities to encourage sustainable bioenergy supply chain mobilization

Technical
- Research and development of improved technologies and supply chain optimization
- Technology transfer from experienced regions to regions with minimal bioenergy deployment
- Learning-by-doing (e.g., starting small and scaling)
- System design optimizing local conditions and using existing infrastructure
- Biomass production that is aligned with existing silvicultural and agricultural practices

Institutional
- Clear and consistent policy definitions and goals for renewable energy
- Coordinated policies for forestry, agriculture, renewable energy and climate change
- Cooperative organizational structures along the supply chain
- Internationally accepted sustainability standards
- Good governance systems to guide sustainable practices
- Guaranteed long-term support (e.g., feed-in tariffs, renewable energy credits, subsidies)

Social & economic
- Competitive business & available financial investment
- Broad societal stakeholder consensus on pathways to achieve energy system transformation

Social, economic and environmental opportunities

- Reduced greenhouse gas emissions through replacement of fossil fuels
- Increased domestic energy security
- Rural economic development and employment opportunities
- Potential improvement in local environmental conditions
- Possible contribution to improving renewable resource management practices
- Added value to lands maintained in forestry and agriculture

Figure 7.3. Summary of opportunities identified.

7.8 CONCLUSION

The widespread mobilization of commercially viable, sustainable, bioenergy supply chains faces a number of significant barriers, as described above and in each of the case studies analyzed in this report. Specific opportunities to overcome these barriers have been identified, as have opportunities to improve the environment, livelihoods, and local economies through the deployment of sustainable bioenergy systems.

Realizing these opportunities will require sufficient political will, stakeholder cooperation, and a commitment to continued research, development, and technological innovation. Furthermore, good governance systems are critical to ensuring that positive impacts are maximized and sustainability is realized at each point along the various supply chains. With these mechanisms in place, sustainable bioenergy can play a more significant role in reducing reliance on fossil fuels, increasing domestic energy security, and improving rural economies in many regions of the globe.

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IEA Bioenergy

IEA Bioenergy is an international collaboration set up in 1978 by the IEA to improve international co-operation and information exchange between national RD&D bioenergy programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use. Currently IEA Bioenergy has 22 Members and is operating on the basis of 13 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

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