Growing a sustainable biofuels industry: economics, environmental considerations, and the role of the Conservation Reserve Program

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Abstract
Biofuels are expected to be a major contributor to renewable energy in the coming decades under the Renewable Fuel Standard (RFS). These fuels have many attractive properties including the promotion of energy independence, rural development, and the reduction of national carbon emissions. However, several unresolved environmental and economic concerns remain. Environmentally, much of the biomass is expected to come from agricultural expansion and/or intensification, which may greatly affect the net environmental impact, and economically, the lack of a developed infrastructure and bottlenecks along the supply chain may affect the industry’s economic vitality. The approximately 30 million acres (12 million hectares) under the Conservation Reserve Program (CRP) represent one land base for possible expansion. Here, we examine the potential role of the CRP in biofuels industry development, by (1) assessing the range of environmental effects on six end points of concern, and (2) simulating differences in potential industry growth nationally using a systems dynamics model. The model examines seven land-use scenarios (various percentages of CRP cultivation for biofuel) and five economic scenarios (subsidy schemes) to explore the benefits of using the CRP. The environmental assessment revealed wide variation in potential impacts. Lignocellulosic feedstocks had the greatest potential to improve the environmental condition relative to row crops, but the most plausible impacts were considered to be neutral or slightly negative. Model simulations revealed that industry growth was much more sensitive to economic policy than land-use scenarios—similar volumes of biofuels could be produced with no CRP as with 100% utilization. The range of responses to economic policy was

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substantial, including long-term market stagnation at current levels of first-generation biofuels under minimal policy intervention, or RFS-scale quantities of biofuels if policy or market conditions were more favorable. In total, the combination of the environmental assessment and the supply chain model suggests that large-scale conversion of the CRP to row crops would likely incur a significant environmental cost, without a concomitant benefit in terms of biofuel production.

Keywords: lignocellulosic, biofuels, environmental impacts, systems analysis, sustainability, subsidy, Renewable Fuel Standard, Energy Independence and Security Act, Conservation Reserve Program, land use

Online supplementary data available from stacks.iop.org/ERL/8/025016/mmedia

1. Introduction

In the US, corn ethanol production increased rapidly since 2000 in response to growing demand and is now capped at 57 billion l (15 B gal). This cap is set by volume requirements under the 2007 Energy Independence and Security Act (EISA) and the associated Renewable Fuel Standard (RFS) and update (RFS2) [1]. Current corn ethanol production nearly meets these levels, with roughly 45% of the corn crop in 2011 consumed to meet the 50 B l (13.2 B gal) mandated [2]. Thus, much of the increase in biofuel production to meet the 136 B l (36 B gal) of total renewable fuel in 2022 is expected to come from lignocellulosic based biofuels.

In a recent review Robertson et al [3] estimate that 608 MMt of biomass will be needed to meet the US cellulosic ethanol demand in 2022 [3]. Of that, approximately 109 MMt of forest products [4, 5], 90 MMt of municipal solid waste [6], and 55–110 MMt of corn stover [3, 7] is projected to be available currently. This leaves 299 MMt of biomass required, which could increase to 518 MMt under more pessimistic assumptions. With a central estimate of 400 MMt, the question becomes where does this biomass come from and under what environmental and economic conditions?

Most projections agree that the increase in feedstock production for biofuels will need to come from either agricultural intensification on existing cropland, expansion of agriculture onto marginal or conservation lands, or both [8, 9]. Though earlier estimates saw little evidence of such shifts [10], more recent work suggests large-scale expansion is occurring especially in the Dakotas and Iowa [11]. If EISA targets are to be met, the coming years will likely show continued expansion. Several recent reports from the National Academies, the Environmental Protection Agency (EPA), and other institutions and research groups highlight that where and how these land-use changes occur will have a dramatic effect on the net environmental impact of a growing biofuels industry [1, 12, 13]. If intensification on existing agricultural lands or lands recently in production is sufficient, then net impacts may be relatively minor; if expansion on uncultivated land or land not recently in production is required, net impacts will likely be substantial [1, 3].

Lands enrolled in the Conservation Reserve Program (CRP) represent a potentially large land base for agricultural expansion for biofuels [8, 14]. These uses, however, should be carefully weighed against the environmental benefits already provided [15]. In the 2010 fiscal year, for example, CRP land prevented losses of sediment, nitrogen, and phosphorous by an estimated 220 MMt, 275 M kg, and 55 M kg respectively [15]. Greenhouse gases were estimated to have been reduced by 52 MMt from CO2 sequestered on these lands and from avoided energy and fertilizer use. CRP also provides habitat for wildlife. It is estimated that CRP contributed to a net increase of prairie pothole ducks by 2 million individuals per year since 1992 (30% increase), and contributed to halting a decline in sage grouse populations, an important species for recreational hunters as well as ecosystems [15].

It is unclear to what degree we can expand the biofuels industry to provide energy security, GHG emissions reduction, and rural development, while mitigating the impacts from agricultural intensification. Growth in the industry has not kept pace with expectations—EPA has issued waivers for all years covered under the RFS2 to date, with final volumes for cellulosic biomass in 2012 at only 1.7% of the original schedule (8.65 M gal as opposed to 500 M gal) [16]. These patterns underscore challenges that remain across the supply chain, and elicit concern on the utility of marginal lands for biomass expansion. Growth of the lignocellulosic biofuels industry will be a complex process, requiring development and adoption of new agricultural practices for feedstock growth and harvest, investment and development of pilot- and commercial-scale biorefineries that are profitable and attract further investment, and infrastructure to deliver fuels incompatible with existing gasoline pipelines, to name a few [17, 18], regardless of the potential GHG benefits.

Here we will address some of these issues by focusing on a central two-part question—what is the range of possible impacts from land-use change from biofuel production especially as they relate to CRP; and how large is the potential gain in terms of gallons of biofuel produced under a variety of CRP usages? While the former approximates an environmental cost, the latter approximates a societal benefit. Section 3.1 focuses on the key findings of the EPA's First Triennial Report to Congress [1], with an additional qualitative synthesis of the impacts at the feedstock production phase. Section 3.2 examines the role that various amounts of CRP could play in the development of the cellulosic biofuels industry, using a systems analysis...
model developed by the National Renewable Energy Lab (NREL)—the Biomass Scenario Model (BSM 3.0) [18].

2. Materials and methods

2.1. Overview of environmental assessment

The US Environmental Protection Agency (EPA) completed an assessment of the environmental and resource conservation impacts associated with the biofuels industry in a Report to Congress in December of 2011 [1]. This report constituted a comprehensive review of scientific literature published through July 2010, including more than 500 peer reviewed publications, to summarize the state of knowledge across the biofuel supply chain, including current and anticipated future impacts from feedstock production, feedstock logistics, and biofuel production, distribution, and use. Environmental impacts focused on six categories of concern (water quality, water quantity, soil quality, air quality, terrestrial and aquatic biodiversity, and invasion of feedstock crops) and five feedstocks (corn, soy, corn stover, perennial grasses, and woody biomass). Here, we focus on the feedstock production stage, because impacts on most of the environmental end points examined were found to be dominated by this early stage. Algae were also considered, but for the purpose of this analysis on CRP we restrict our focus to the five feedstocks above. Perennial grasses were generally represented by switchgrass (Panicum virgatum) and giant miscanthus (Miscanthus × giganteus). Woody biomass ranged from forest thinning to cultivation and harvesting of long and short-rotation woody crops, especially pine (Pinus), poplar (Populus) and willow (Salix). The impacts of harvesting corn stover were considered separate from those of corn cultivation itself.

The review of the literature served as a starting point for a qualitative synthesis of the information to describe the range, magnitude, uncertainty, and most plausible environmental outcome of feedstock production according to present knowledge. We describe these attributes for each of the six categories of concern. The synthesis was based upon a consensus view of the authors of the report given the broad range of assumptions found in the scientific literature, and follows similar protocols to the Millennium Ecosystem Assessment [19]. A more quantitative environmental lifecycle assessment [20–23] was discussed, but it was determined that the modeling platforms and data input requirements were not sufficiently developed to support such an effort nationally for end points other than GHGs (already covered in [24]).

For the qualitative synthesis, we examined the maximum potential range of domestic environmental impacts associated with the production of biofuels under RFS2 described in the literature. Range extremes were determined by examining reasonable conditions under which a ‘most negative’ and ‘most positive’ environmental impact could arise (table 1). Between the range extremes are numerous specific combinations of management approaches, regional influences, land-use changes, technologies, and other considerations, which create a distribution of potential impacts within the presented range. Our uncertainty estimates are based upon expert judgment, including the amount of literature, the agreement within the literature, whether it is consistent with fundamental process knowledge, and the validity and agreement of underlying assumptions [25]. Finally, we describe the most plausible impacts within the maximum potential range based on sets of assumptions commonly considered in the literature and based on increased feedstock and fuel production in response to the RFS2 schedule (table 1). Information published after the July 2010 cutoff for the Report is mentioned where appropriate.

2.2. Overview of biomass scenario model and analytical approach

2.2.1. System architecture and input sources. Here we give a brief overview of the BSM model structure, and provide a more thorough description of the model in the supplementary material (stacks.iop.org/ERL/8/025016/mmedia) and in other publications [18]. The BSM has been developed since 2005 in coordination with the National Renewable Energy Lab (NREL), the US Department of Energy (DOE), and affiliated contractors and sponsors. The BSM is a system dynamics model built on the STELLA software platform, designed to examine the complex technological, economic, and logistical development and dynamics of the entire industry. It includes a series of 10 dynamically interconnected modules (figure 1) that include feedstock supply, feedstock logistics, feedstock conversion, inventory and pricing (of biofuels), distribution logistics, dispensing stations, fuel use, vehicles, biofuel imports, and the petroleum industry. These modules receive and react to information in a complex, nonlinear fashion that depends on, among other things, industrial learning, project economics, installed infrastructure, consumer choices, and investment dynamics. Much of the logic and information underpinning the BSM has been developed with industry and federal input through an iterative process of refinement. The BSM is not a predictive model, rather it represents the dynamic behavior of the industry according to our present understanding. It is used here to explore various potential trajectories of industry growth in a general way, not to make specific predictions on industry development.

The geographic structure of the BSM uses the 10 US Department of Agriculture (USDA) farm production regions as a basis (supplementary figure 1 available at stacks.iop.org/ERL/8/025016/mmedia), which facilitates analysis of regional differences in key variables. The model is solved numerically at a sub-monthly level and reports output for the timeframe of 2005–50. The feedstock production and land allocation module is based primarily on POLYSYS [26, 27], and simulates the production of five commodity crops (corn, wheat, soybeans, cotton, and other grains) five biomass crops for biofuels (herbaceous perennials, woody perennials, agricultural residue, urban residue, and forest residue), as well as hay and an option for no crop. The decision on what to plant is based on a farmer decision submodule, that considers allocation dynamics, new agricultural practices, markets, and
Table 1. Assumptions considered in the EPA’s first Report to Congress to bracket anticipated environmental impacts from biomass production from two first-generation (corn starch, soybean) and three second-generation (corn stover, perennial grasses, woody biomass) feedstocks. Table below and referenced sections therein are from [1].

| Feedstock       | Environmental impact per unit area                          |
|-----------------|-------------------------------------------------------------|
| **Corn starch** | Most negative: Corn grown with conventional tillage, irrigation, and high chemical inputs replaces uncultivated land such as that in the Conservation Reserve Program (CRP)  |
|                  | Negligible: Existing corn grown with conservation practices diverted to biofuel supply chain. No change in land use.  |
|                  | Most positive: Existing corn grown with conservation practices diverted to biofuel supply chain. No change in land use.  |
|                  | Most plausible: Conventionally managed, tilled corn in regions not requiring irrigation replaces conventionally managed, no-till soy or other row crops. Overall trend as reported by USDA is increasing acreage of corn planted since 2005 (see section 3.2.3 in [1])  |
| **Soybean**     | Most negative: Soy grown with conventional tillage, irrigation, and high chemical inputs replaces uncultivated land such as that in the CRP  |
|                  | Negligible: Existing soy grown with conservation tillage diverted to biofuel supply chain. No change in land use.  |
|                  | Most positive: Soy grown with comprehensive conservation practices replaces corn grown with conventional tillage and high chemical inputs  |
|                  | Most plausible: Existing soy grown with conservation tillage diverted to biofuel supply chain to meet relatively small volumetric RFS2 biodiesel requirements. Overall trend as reported by USDA is relatively stable acreage of soybeans planted since 2005 (excluding 2007, see section 3.2.3 in [1])  |
| **Corn stover** | High rate of stover removal on highly erodible land requiring additional equipment passes after corn grain harvesting replaces same with no stover removal  |
|                  | Negligible: Existing corn with appropriate rate of stover removal to minimize erosion, soil organic matter loss, and fertilizer application given site-specific characteristics replaces same with no stover removal. Single-pass harvest with corn  |
|                  | Most positive: Stover removal at ‘logistically removable’ rate (see USDA’s Billion Ton Study), without considering local characteristics, from conventionally managed, tilled corn in regions not requiring irrigation replaces same with no stover removal. Impacts shown are beyond corn cultivation and from separate pass harvest  |
| **Perennial grasses** | Invasive perennial grasses established with conventional tillage and grown with a short planting interval, high rates of chemical inputs, and irrigation replace uncultivated land such as that in the CRP  |
|                  | Negligible: Perennial grasses from currently mowed pasture or other managed grasslands diverted to biofuel supply chain. No change in land use  |
|                  | Most positive: Non-invasive perennial grasses established with no till and grown with a long replanting interval, low chemical inputs and no irrigation replace irrigated corn grown with conventional tillage and high chemical inputs  |
|                  | Most plausible: Switchgrass grown with fertilizer in regions not requiring irrigation replaces CRP and other low management lands. Switchgrass (unlike Giant Miscanthus) cultivated for farm-scale studies on CRP in many areas of US (see section 3.3.3 in [1])  |
| **Woody biomass** | Invasive short-rotation woody crops (SRWC) with short replanting intervals, high chemical inputs, high isoprene emissions, and no coppicing replace mature, managed, low-isoprene-emitting tree plantations  |
|                  | Negligible: Removal of managed forest harvest residues at rates that maintain soil organic matter and minimize erosion replaces residues left on site  |
|                  | Most positive: Non-invasive, coppiced SRWC with long replanting intervals, low chemical inputs, and low isoprene emissions replace non-coppiced, managed forests with short replanting intervals and high isoprene emissions. OR low to moderate rates of forest residue removal or thinning replaces residues left on site  |
|                  | Most plausible: Removal rate of managed forest harvest residues without considering local characteristics replaces residues left on site. This is the greatest source of woody biomass assumed under the RFS2 RIA (EPA 2010b).  |
prices. In short, land is allocated towards what is simulated to bring the greatest expected net revenue, incorporating expected crop yields, price (i.e., grower payment), and production costs among other factors. Additional modules are described in more detail in the supplementary material. Because the BSM was designed by NREL for analysis and decision support for US decision makers, units are in English. Nonetheless, conversions are made in the main text to SI for clarity.

A major new version of BSM was recently completed (BSM 3.0) and is used in this analysis. BSM 3.0 includes infrastructure-compatible fuels and butanol (termed ‘drop-in’ fuels), in addition to ethanol. Detailed information on BSM is available from previous publications, most of which apply equally to BSM 2.0 (no drop-in fuels) and BSM 3.0 [17, 18]. The BSM 3.0 model is documented in [28], and key sources for major changes are shown in table 2.

2.2.2. Land use and policy scenarios explored. The land-use scenarios and policy scenarios described here are used to explore the effects of different land bases and subsidy schemes on the development of the biofuels industry. There were seven land-use scenarios and five policy scenarios explored (table 3). The land-use scenarios generally described the degree of conversion of CRP lands to the agricultural land base, and whether existing biomass on CRP land was merely harvested for biofuel biomass, or CRP land was converted to an energy cropping system. Lands could either be ‘migrated’ to the...
Table 2. Summary of input data to BSM and changes for BSM 3.0 (additional information available online).

| Module name                | Primary functions                                                                 | Selected major sources                                                                 | BSM 3.0 versus BSM 2.0             |
|----------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-----------------------------------|
| Feedstock supply           | Simulates production of biomass (herbaceous and woody perennials; agricultural, urban, and forest residues) and crops (corn, wheat, soybeans, cotton, other grains) based on farmer decisions. Allocates land based on relative profitability and policy to 5 commodity crops, hay, pasture, or CRP | POLYSYS [26, 27], DOE Billion Ton Study [4] and update [5]                              | No major change                   |
| Feedstock logistics        | Models harvesting, collection, storage, preprocessing, and transportation of biomass feedstocks from field (or forest) to biorefinery | Integrated Biomass Supply and Logistics (IBSAL) [49]                                    | No major change                   |
| Feedstock conversion (see figure 1) | Represents transforming feedstock into ethanol, butanol, and refinery-ready fuels (gasoline, diesel, jet fuel) for use as refinery feedstocks, blendstocks, or finished products | Conversion pathway design reports                                                     | Added butanol and refinery-ready fuels |
| Inventory and pricing      | Accounts for biofuels inventories and prices                                        | None—accounting module                                                               | No major change                   |
| Downstream modules for ethanol | A set of ethanol-specific modules address distribution logistics, dispensing stations, fuel use, and vehicle scenarios to provides dynamics of build-out of ethanol-capable infrastructure from conversion plant gate to fuel use in vehicles | NACS, BSM analysis, BAU scenario based on Annual Energy Outlook (EIA)                 | No major change; modules apply to ethanol, not refinery-ready fuels |
| Biofuel imports            | Represents imports and exports of ethanol based on price                             | BSM analysts                                                                         | No major change                   |
| Petroleum industry         | Provides crude oil price scenarios and other market data                             | BSM analysts                                                                         | No major change                   |

agricultural land base or ‘dedicated’ to biomass production. If CRP land was ‘migrated’, it could be used for whatever was most economical (i.e. including corn and other row crops). If CRP was ‘dedicated’, it could only be used for energy biomass production, but only under conditions and regions where it was profitable. Thus, CRP lands ‘dedicated’ could only be in CRP or in the production of biomass for biofuels (if it were profitable)—they could not go into annual crop production. In short, CRP lands are determined to be profitable if the revenue from selling the biomass to market (farm-gate price) exceeds the cost to growing the biomass (e.g. from clearing, planting, managing, and harvesting). The five economic scenarios generally describe the degree of financial support for the biofuels industry such as subsidies and loan guarantees (table 3, figure 2), with emphasis on the conversion, logistics, and end use stages of the supply chain. Specific subsidy levels were quantified in consultation with Agency and industry experts, and do not represent specific policies under consideration. Collectively they were designed to bracket a plausible set of potential future biofuels policy environments, to explore industry growth and evolution. The BSM is responsive to a number of potential policies that improve the financial prospects of biofuels, including point of production ethanol subsidies, feedstock subsidies, capital cost subsidies, loan guarantees, downstream distribution and storage subsidies, and subsidies at the pump (‘point of use’). Details on the magnitude and timing of these economic subsidies for these analyses are shown in figure 2, and elaborated in the supplementary material (available at stacks.iop.org/ERL/8/025016/mmedia).

3. Results

3.1. Environmental assessment

A developing biofuels industry can have a wide range of potential impacts on all environmental end points of concern (figure 3). Factors that account for this variation include regional climate, soil type, topography, agricultural and...
management practices, prior land use, along with a host of others.

In the case of most impact categories, lignocellulosic feedstocks tend to have the greatest potential for improving environmental condition. This positive environmental outlook, however, was not found to be the most plausible. This is largely because the most positive impact of cellulosic feedstocks relies upon changes in land use and conservation measures that are not generally recognized as likely in the literature (e.g. conversion of intensively managed corn to conservation managed switchgrass, table 1). The most plausible impacts of cellulosic feedstocks tend to be negligible or slightly negative, in contrast with conventional feedstocks (corn and soy) which range from negligible to intermediate negative. Much more certainty was found in the literature for first-generation feedstocks than second-generation feedstocks; and, impacts on invasiveness, biodiversity, and air quality was less certain than impacts on soil and water for second-generation feedstocks.

Water quality had the greatest potential to be negatively affected by increasing cultivation of corn and soy compared with other changes in crop production considered, and the greatest potential for improvement if perennial grasses and woody biomass were grown. Alternative outcomes were also possible though, with a negative effect on water quality if perennial grasses grown with high fertilizer applications replace CRP, and no direct environmental effect from corn replacing other row crops that generally require fewer chemical inputs, resulting in a net decrease in water quality.

Table 3. Overview of scenarios.

| Label | Name | Description |
|-------|------|-------------|
| A (BAU) | Base: business as usual | No changes in land base |
| B (D40) | Dedicate CRP (40%) | Dedicate 40% of CRP to lignocellulosic biomass production, no additional harvesting on remaining 60%<sup>a</sup> |
| C (D100) | Dedicate CRP (100%) | Dedicate 100% of CRP to lignocellulosic biomass production |
| D (H) | Harvest CRP | Harvest 100% CRP for lignocellulosic biomass, no additional management inputs |
| E (M40) | Migrate CRP (40%) and cultivate | Migrate 40% of CRP to active agricultural land base, no additional harvesting on remaining 60%<sup>a</sup> |
| F (M70) | Migrate CRP (70%) and cultivate | Migrate 70% of CRP to active agricultural land base, no additional harvesting on remaining 30% |
| G (M100) | Migrate CRP (100%) and cultivate | Migrate 100% of CRP to active agricultural land base |

Subsidy scenarios

| Label | Name | Description |
|-------|------|-------------|
| 1 (M) | Minimal | Only the $0.45 blenders credit until 2012, after which no economic support |
| 2 (Et) | Ethanol-only | $2.65 gal<sup>−1</sup> at plant gate (<2018), $0.15 thereafter, 60% FCI for pioneer plants (<2015), 70% loan guarantee for pioneer plants (<2015), $0.45 gal<sup>−1</sup> blenders credit (<2012<sup>b</sup>), $0.15 gal<sup>−1</sup> downstream for distribution and storage (<2023), $0.50 gal<sup>−1</sup> at the pump (<2021) |
| 3 (RFS2) | RFS2-focused | For ethanol: $2.25 gal<sup>−1</sup> at plant gate (<2017), 70% for all FCI and loan guarantees (<2017), $0.45 gal<sup>−1</sup> blenders credit (<2012), $1.25 gal<sup>−1</sup> at the pump (<2025); for fungible fuels: $2.65 gal<sup>−1</sup> at plant gate (<2024, $1.00 thereafter), 70% for all FCI and loan guarantees (<2022). Annual spending capped at $10 B |
| 4 (Out) | Output-focused | For ethanol: $2.65 gal<sup>−1</sup> at plant gate (<2017, $0.15 thereafter), 60% for FCI for pioneer (<2022), 70% for all loan guarantees (<2022), $0.45 gal<sup>−1</sup> blenders credit (<2012), $0.50 gal<sup>−1</sup> at the pump (<2021); for fungible fuels: $2.65 gal<sup>−1</sup> at plant gate (<2019, $0.15 thereafter), 100% FCI for fast pyrolysis (FP) pioneer plants (<2019, 60% thereafter), 30% FCI for FP commercial plants (<2017), and 100% for all FP loan guarantees (<2031). Annual spending capped at $10 B |
| 5 (Div) | Diversity-focused | For ethanol: $1.00 gal<sup>−1</sup> at plant gate (<2018), 60% FCI for pioneer plants (<2018), 70% for all loan guarantees, $0.45 gal<sup>−1</sup> blenders credit (<2012), $0.50 gal<sup>−1</sup> at the pump (<2021); for fungible fuels: see figure 2 for details. Annual spending capped at $10 B |

<sup>a</sup> When CRP is ‘migrated’ to the active agricultural land base, market conditions determine the eventual use of that land. For example, whether it more profitable to grow lignocellulosic biomass or a commodity crop such as corn will determine the farmers’ decisions. When CRP is ‘dedicated’ it is fixed for lignocellulosic production in the BSM if that is profitable.

<sup>b</sup> Expiration date shown, beginning in 2005, where otherwise noted.
Figure 2. Details of the five subsidy scenarios (columns) simulated by pathway (rows) and year (abscissa). Subsidy types are color coded, where length denotes the period of performance, and thickness approximates magnitude (either per $ or as a %). As an example of how to read the figure, for Scenario 3 (RFS2-focused), there is a point of production subsidy (blue bars) for all fungible fuels of $2.65 gal−1 from 2010 to 2024, after which the subsidy declines to $1.00 gal−1 until 2031.

In addition, perennial grasses and woody biomass are not anticipated to displace corn production, where the greatest improvements might be seen, and instead are expected to be grown with chemical inputs on marginal land such as CRP (for perennial grasses) or on tree plantations (for woody biomass). Their dense perennial root mat (and generally lower fertilization rates) mean water quality is not anticipated to be altered, though this remains an understudied topic. Impacts from soybean for this and other environmental end points is anticipated to be neutral because diversion of existing production rather than expansion is anticipated to be the most plausible outcome. However, subsequent economic impacts from diversion of US soybean to biofuel, including increased prices of feed for animals, and alterations in the global soybean trade, could have additional effects domestically and internationally. These impacts were, however, generally beyond the scope of this report.

Water quantity followed similar trends, with the greatest relative impairments possible from cultivation of corn and soy and the greatest relative improvements possible from perennial grasses. Countervailing patterns were also possible. However, as before, the most plausible outcome was anticipated to be neutral for most feedstocks, as corn and soy are predominantly rain fed, and woody acreages are anticipated to be rain fed as well. Perennial grass cultivation however, was anticipated to have a low negative effect, because monotypic stands of switchgrass and Miscanthus are anticipated to have higher cumulative evapotranspiration rates than either corn or mixed stands primarily because of their longer growing season, reducing water availability for other uses [29, 30].

Relative impacts on soil quality were primarily determined by land conversion and management practices in the new production areas. When CRP conversion was assumed, negative impacts were anticipated, whether for corn, soy, or perennial grass production. Positive effects were possible under some second-generation feedstock scenarios as well, though these were not considered likely in the case of perennial grasses (i.e. replacement of rowcrops). The most plausible impacts were intermediate from these extrema, with negligible effects anticipated from diversion of soy, and (over the long term) from expansion of switchgrass replacing low-productivity CRP. More recent analyses [31] suggest that these expectations on the long-term effects of switchgrass replacing CRP may depend on the rate of fertilization. At low fertilization rates ($\leq 45$ kg N ha$^{-1}$) there is a net loss of soil carbon and a net emission of GHGs, while at higher rates there was a net increase in soil carbon and a net sequestration of GHGs due to enhanced soil carbon sequestration. Corn stover was anticipated to have a moderately negative effect, with market conditions determining removal rates rather than optimizing to minimize erosion or soil organic matter loss.
Figure 3. Graphical summary of the environmental assessment of first-generation (1) and second-generation (2) feedstocks at the feedstock production stage on six environmental end points. Impacts were evaluated on a per unit area basis conditional on assumptions in table 1. Bar length, diamonds, and shading are based on author consensus (EPA 2011). Assumptions reflect land use and management practices often considered in the literature, and are not meant to convey likelihood of occurring in the future.

3.2. BSM modeling analysis

We explored seven land use and five policy scenarios as described above (table 3); however the differences in modeling results between the two extreme cases (Base and 100% CRP Migrated or Dedicated) were relatively minor because of bottlenecks and negative feedbacks in the supply chain. Because of this we only display the Base and 100% Migration cases, with intermediate effects for intermediate rates of migration. Comprehensive figures are shown in the supplementary material (available at stacks.iop.org/ERL/8/025016/mmedia).

3.2.1. Land use and biomass production. Modeled land use was relatively stable through time, though results varied more by economic scenario than by land-use scenario (figure 4, note differences among rows and similarities among columns). By 2030, under the Base scenario (figure 4, left column) no cellulosics developed under the Minimal subsidy scenario and little developed under the Ethanol-only scenario (<5 M acres, <2 M ha), while 34, 38, and 26 M acres (14, 15, and 11 M ha) developed under the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Roughly half of these increases in cellulosics came from decreases in annual cropland, with the remainder roughly equally from reductions in hay and pasture. 100% migration of CRP to the agricultural land base (figure 4, right column) resulted in increased annual crops from 2010–2020 in all scenarios and increasing cellulosic crops from 2020–2030 in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively.
Figure 4. Changes in land use (in M acres) from 2010 to 2031 for the five economic scenarios considered (rows) and three of the land-use policies considered (left column: base, center: 100%-dedicated, right: 100%-migrated).

in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. In these cases almost all of the increase in cellulosics came at the expense of CRP (roughly 70% on average) with a much lesser contribution from pasture or hay. Cropland actually increased by 1.6 M acres also at the expense of CRP. When CRP land was forced in the model to be available for cellulosic production but not for annuals production (i.e. 100% Dedicated scenario, supplementary material) all results were nearly identical to the Base scenario. This occurred primarily because growing biomass for biofuels on CRP land was not cost-competitive, but it was cost-competitive to grow annuals on CRP land, if that option was available. Comparing rows, under the Minimal policy and Ethanol-only policy, increased migration of CRP resulted primarily in increased annual crop production. Hereafter we focus on the Base and 100% Migrated land-use scenarios because all other land-use scenarios are close or intermediate to these.

Regional patterns of land use also showed more variation among economic scenarios than among land-use scenarios (2030 shown in supplementary figures 7–9 (SF7–9 available at stacks.iop.org/ERL/8/025016/mmedia)). The small amount of cellulosic production in the Ethanol-only scenario was from the Pacific, Appalachian, and Southeast regions (forest residue). When substantial growth of cellulosic production occurred (i.e. in economic scenarios RFS2-focused, Output-focused, and Diversity-focused scenarios), it did so predominately in the Northern Plains, Southern Plains and Corn Belt regions and to a lesser degree elsewhere.

Cellulosic biomass production, as with land use, was also driven more by economic scenarios than land-use scenarios (figure 5). No cellulosic biomass was produced in the Minimum subsidy scenario (figures 5(a) and (b)), and only forest residue was produced in any substantial quantities in the Ethanol-only scenario (figures 5(c) and (d); 79 and 77 M short tons respectively in 2030 (72 and 70 MMt)). After an initial (2010–2020) similar growth period in the production of forest residue, the RFS2-focused (figures 5(e) and (f)), Output-focused (figures 5(g) and (h)), and Diversity-focused (figures 5(i) and (j)) scenarios showed substantial growth in biomass production, totaling 410, 424, and 332 M short tons respectively in 2030. Most increases came from herbaceous perennials, but agricultural and urban residues also contributed. By 2030, herbaceous perennial production in the Base scenario was 219, 229, and 147 M short tons (199, 208, and 133 MMt) in the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively. Herbaceous biomass increased to 236, 255, and 176 M short tons respectively (214, 231, and 160 MMt) in 2030 with 100% migration of CRP and total cellulosic biomass was 425, 453, and 362 M short tons respectively. Thus, there was an average of a 6.4% increase in total cellulosic biomass from using 100% or CRP. Woody biomass from dedicated perennial energy crops did not make
Figure 5. Biomass produced (in million short tons) through time from 2010 to 2031 for the five economic scenarios considered (rows) and two of the land-use policies considered that bracketed model output (left column: base, right: 100%-migrated).

up a discernible fraction of biomass produced under any scenario examined.

Regional patterns (figure 6, 2030 shown) also followed land-use patterns. Under the Ethanol-only scenario, most cellulosic biomass came from forest residue in the Appalachian, Pacific, Gulf States, and Southeastern regions. Lesser contributions also came from forest residue in several other regions, herbaceous perennials in Appalachia, and from urban residue in the Southeast, Appalachian, and Corn Belt regions. Under the RFS2-focused (figures 6(e) and (f)), Output-focused (figures 6(g) and (h)), and Diversity-focused (figures 6(i) and (j)) scenarios, most of the cellulosic biomass came from herbaceous perennials in the Northern and Southern Plains, from roughly equivalent contributions of herbaceous perennials and agricultural residue in the Corn Belt, and from forest residue from many regions. Urban residue also contributed from the east and west coast regions.

Annual crop biomass (corn, soy, wheat, and other grains) also increased over the period of the simulation. Increases in annual biomass were primarily from increases in corn and soy from yield increases in all cases (2% assumed), and from yield increases as well as acreage increases where CRP migrated to the agricultural base (supplementary material).

3.2.2. Biofuel production. Under the Minimum (figures 7(a) and (b)) and Ethanol-only scenarios (figures 7(c) and (d)), there was no dramatic expansion of the biofuel industry. In the former, starch ethanol from corn dominated, while in the latter starch ethanol from corn and cellulosic ethanol from primarily forest residue co-dominated. Production volumes mandated by RFS2 were not met by 2030 and reached roughly 12 and 20 B gal (45 and 76 B l) for the Minimal policy and Ethanol-only policy, respectively, regardless of CRP usage. Under all three of the RFS2-focused (figures 7(e) and (f)), Output-focused (figures 7(g) and (h)), and Diversity-focused (figures 7(i) and (j)) scenarios, the 36 B gal production volumes mandated by EISA were nearly met by 2030,
Figure 6. Regional patterns of biomass produced in 2030 (in short tons) for the five economic scenarios considered (rows) and two of the land-use policies considered that bracketed model output (left column: base, right: 100%-migrated). Results are displayed by the ten USDA farm production regions.

primarily from an increase in cellulosic drop-in fuels and a steady base of starch ethanol. Total biofuel produced in 2030 for the Base scenario was 35, 49, and 35 B gal (132, 185, and 132 B l) for these three scenarios respectively. As before, 100% CRP migration did little to augment production volumes (36, 51, and 37 B gal in 2030 for the RFS2-focused, Output-focused, and Diversity-focused scenarios respectively). There was a notable transition from cellulosic ethanol growth in the early years (e.g. 2015–2023), to cellulosic drop-in fuels in the later years, which took over market share once that industry matured. By 2030 cellulosic ethanol only made up 5–10% of the biofuel produced across these three scenarios.

Regional patterns (figure 8) followed national trends. By 2030 under the Minimum scenario (figures 8(a) and (b)), starch ethanol from the Corn Belt, Northern Plains, and Lake States regions dominated. For the Ethanol-only scenario (figures 8(c) and (d)), cellulosic ethanol from forest residue in several regions augmented this corn starch ethanol. Under the RFS2-focused (figures 8(e) and (f)), Output-focused (figures 8(g) and (h)), and Diversity-focused (figures 8(i) and (j)) scenarios, most biofuel came from a combination of cellulosic drop-in and starch ethanol fuel in the Northern Plains, Corn Belt, and Lake States regions. Lesser contributions came from other regions, which were often also dominated by cellulosic drop-in fuels, except in the Appalachia and Delta States regions in which cellulosic ethanol also contributed substantially. Increased CRP acreage did little to alter the regional patterns.

4. Discussion

Generally, the combination of the environmental assessment and the BSM modeling suggest that large-scale conversion
of CRP to row crops would likely incur a significant environmental cost, without a concomitant benefit in terms of biofuel production.

Many of the most negative environmental impacts were found to be involved with conversion of conservation lands such as CRP to industrial agricultural production. Agricultural intensification and extensification, whether for food crops or energy crops, have many impacts on GHG balances, nitrogen fluxes in the environment, regional water balances, and wildlife [3]. Indeed, conversion of CRP to no-till corn and corn–soy rotations incurs a carbon debt of 40 and 29 years, respectively, payback times which triple under conventional tillage [32]. Harvesting CRP without such conversion incurs no local carbon debt. However, other environmental impacts synthesized here can certainly occur especially if chemical inputs are used to grow cellulosic biomass. For example, nitrate and phosphorus runoff from existing switchgrass fields was comparable to that from no-till corn that received twice the fertilizer in an Alabama site [33]. Similarly high rates have been reported for Miscanthus [34, 35]. Although plant biodiversity on CRP lands is lower than native grasslands, it is still substantial [36], and can provide habitat for many other species [9]. Part of the uncertainty surrounds whether the benefits of CRP will be continued under former CRP lands cultivated for biofuels, which could be managed very differently. These issues remain little studied aside from GHGs, and require further investigation before confidence can be assigned to expectations and to avoid trading off one environmental benefit (e.g. GHG reductions) for another cost (e.g. increased Gulf hypoxia).

Our qualitative synthesis suggests that although first-generation feedstocks (such as corn and soybean) had a great risk for negative environmental effects, the conditions considered most plausible will produce a modest (though still negative) impact. For second-generation feedstocks expectations also appeared exaggerated—while these feedstocks
Figure 8. Regional patterns of biofuel produced in 2030 (in gal) for the five economic scenarios considered (rows) and two of the land-use policies considered that bracketed model output (left column: base, right: 100%-migrated). Results are displayed by the ten USDA farm production regions.

have a great potential for positive environmental effects, under most plausible scenarios impacts were either neutral or slightly negative. These assumptions however are based on the existing assumptions to date available in the literature, and may not reflect actual practices in the field. Quantitative estimates similar to these based on a range of scenarios tailored to region-specific conditions remain to be carried out. However, research in the area of lifecycle analysis and environmental lifecycle analysis indicate tools are under development to expand our understanding of environmental impacts beyond GHGs [21, 22, 37].

It is uncertain whether the biofuel industry to date has been a threat to the CRP program. Since 2007 the CRP program has seen a steady decline in enrolled acreage, from over 36 M acres in 2007 to less than 30 M acres in 2012 (14.6–12.1 M ha) [38]. Aside from the spike in corn prices in 2007, of which only an estimated third was attributed to biofuels [39], recent declines in CRP enrollment since 2008 and expansion of corn production nationally [11] imply that biofuels may be playing a role. However, careful examination suggests that this role may be short lived. The E10 ‘blend wall’ was reached sometime in late 2011 [40] meaning that no more total ethanol could be blended into the transportation fuel mix. The E10 blend wall (combined with a lack of industry alternatives) is the main reason why the Minimal scenario and Ethanol-only scenario showed little growth—there is nowhere for the ethanol to go. The increase to E15 by EPA in January 2011 for cars built after 2000 was intended to relax this bottleneck [41]. However, it appears this relaxation has not yet affected the industry—the first E15 filling station in the country started selling E15 in July 2012 just west of Kansas City [42]. Few have opened since then. Steady increases in corn production (2008–2011, after the 2007 spike) and decrease in CRP acreage may
also be a result of high corn prices for other reasons (e.g., poor production years, drought, storms) rather than from the modest increases needed meet the E10 blend wall. Indeed, a 2011 USDA report [43] found that total enrollment in CRP and the quality of lands enrolled were likely to drop unless program expenditures could keep pace with high commodity prices. The added pressure from corn ethanol was estimated to be minor.

Nevertheless, food and fuel markets are clearly interlinked at this point [44], and a lack of strong connection to date does not eliminate the possibility of one in the future (but see [11]). Indeed, this connection will likely strengthen dramatically if the industry starts to meet volumes targeted by EISA. This pause in industry development associated with the blend wall, however, is an opportune moment to evaluate whether the likely path of development will meet the various goals articulated in EISA 2007. Our analysis of industry growth with the BSM suggests that RFS2-scale volumes can be met with no CRP conversion, and indeed underscores that CRP conversion has little effect on promoting industry growth.

More important than land base was a coordinated economic incentives structure to facilitate growth. For the Output-focused scenario, primary among these were support for Fixed Capital Investment and Loan Guarantees for Fast Pyrolysis, which screening analyses suggested to have favorable long-term technological and economic prospects (supplementary material available at stacks.iop.org/ERL/8/025016/mmedia). For the Diversity-focused scenario (and the RFS-focused scenario), a wider portfolio of subsidies led to similar though not as much growth in the industry as the Output-focused scenario. Aggregate costs for all policies however were not equal. Cursory analyses of the costs of the five policies explored here indicate that the aggregate and annual cost per gallon of gasoline-equivalent output are quite low for the Output-Focus and Diversity-Focus scenarios, at levels similar to the Ethanol-only scenario (supplementary material). The only scenario explored that appeared prohibitively expensive was the RFS2-focused scenario. This was primarily because the industry wasn’t mature enough to meet the earlier target years (requiring large investments to do so), but that if target timelines were relaxed by 5–10 years industry growth was much more cost effective.

We ran supplemental simulations to explore the effect of the recent increase to E15 and found our overall conclusions unaffected. E15 did increase the cellulosic ethanol biofuel produced in all cases (even the Minimum policy, figure 9). However, the increase to E15 merely delayed hitting the blend wall by a few years, and cellulosic drop-in fuels were still necessary to meet the 36 B gal target set by the RFS2. E15 has been slow to come to market for many reasons [42], which could continue to be the case in the near term. In addition, the opportunities for E85 use are insufficient to absorb excess cellulosic ethanol either now or in the foreseeable future without significant increases in E85 vehicle sales and fuel availability.

Even though CRP usage was found to have little effect on biofuels industry growth, there were benefits to its usage at the margin for other commodities. In the BSM, the increase in acreage of herbaceous perennials under the Base scenario came from decreases in pasture, hay, and annuals mostly from less-productive lands (figure 5). Because these reductions in the land base were small compared to the total, there were only minor changes in most food commodity prices, which still tended to decrease through time because of yield increases (figure 10). Hay and cotton prices, however, did show some effects (figure 10). Although there were many differences among regions and scenarios, hay prices generally increased, especially in the Southeast, Southern Plains, and Northern Plains, in line with production areas (supplementary material). Cotton prices also showed an increase towards the latter ends of the simulation. Both of these price increases were mitigated with migration of CRP to agricultural production (figure 10).

The scenarios explored here are not intended to be prescriptive for any detailed policy development, nor are they intended to be projections of expected outcome. The model structure merely represents the state of knowledge of the associated researchers and industry experts to date, and the model output represents the logical outcome of that state of knowledge. A full sensitivity analysis of the BSM is underway at NREL, which will further elucidate the primary drivers of the model. Initial results of this analysis suggests that the model is sensitive to many parameters and feedbacks, including feedstock yield estimates, learning rates among different industry stages, initial cost supports for plant development, as well as the distribution and numbers of E85 vehicles nationwide among others. Many modeling efforts have examined how a growing biofuels industry might alter land-use patterns nationally and internationally, with varying levels of sophistication in several aspects including national versus international markets, detail of ‘downstream’ processes such as infrastructure roll-out, as well as other factors [26, 45–47]. Other studies using POLYSYS and other models indicate that substantial cellulosic biomass and carbon offsets are available to meet EISA [5, 26, 48]. These do not disagree with our findings; rather, the BSM indicates that whether this potential is realized depends strongly on dynamics across the entire supply chain, not just at the agricultural stage which most other modeling platforms focus on to a greater extent (e.g. POLYSYS, FASOM). All of these models provide insight (while none are correct) based on their relative strengths and weaknesses in modeling the various factors affecting this market. The findings presented here are intended to illustrate general properties and tendencies of this complex reticulated system, to shed light on possible developments and intervention points under a range of assumptions.

Growth of the biofuels industry in line with target volumes from RFS2 appears to hinge on the potential for drop-in fuels from cellulosic feedstocks from herbaceous perennials grown primarily in the Midwest, building from current production of starch ethanol from corn, and cellulosic ethanol from wood products in forested regions. Without drop-ins, the industry is limited by blending limits and insufficient E85 opportunities, and ironically, higher fuel efficiencies. The assumptions underpinning the drop-in
industry are uncertain, and range from optimistic to pessimistic (supplementary material), though efforts have been made to identify realistic technological and economic assumptions given the information available. The roughly 30 M acres of CRP available appears to have little impact on industry growth, except for some increased ancillary cotton and hay prices in some regions. Industry development appears to require significant subsidy supports according to the model, though with sufficient breakthroughs in technology and greater adoption of E85 vehicles, such investments might not be necessary.

5. Conclusion

The combination of the environmental assessment and the simulations suggests that large-scale conversion of CRP to row crops would likely incur a significant environmental cost, without a large benefit in terms of biofuel production. Therefore, the current environmental benefits provided by CRP lands should be fully weighed in any full-cost accounting of their potential use. We find that lignocellulosic feedstocks tend to have the greatest potential for improving environmental condition, but that the most plausible impacts are considered to be neutral or slightly negative from agricultural expansion onto marginal land. BSM simulations demonstrate that the magnitude of response to biofuel policy is substantial: results can show long-term market stagnation at current levels of first-generation biofuels under minimal policy intervention, or can show RFS2-scale quantities of second-generation and advanced biofuels if policy or market conditions are more favorable to industry growth. The potential conversion of CRP land to active use (whether for row crops, hay, pasture, or energy crops) has a far smaller range of impacts on the growth of the biofuels industry, but the relaxation of CRP-related constraints does marginally affect
Figure 10. Crop prices (in $ short ton$^{-1}$) through time for the five annual crops simulated (columns) for the five economic scenarios explored (rows) separated by land-use scenarios (blue: base, red: 100% migration).

the mix of feedstocks produced for conversion to biofuels, the timing of their entry into production, and some feedstock and crop prices in some regions.

Overall, our results suggest that EISA volumetric requirements for second-generation biofuels could be met without using CRP lands, and that CRP lands do not greatly promote industry growth. Thus, policies that focus solely on the use of conservation or marginal lands to produce significant quantities of biofuels are not likely to be successful, while the use of economic policies could produce more favorable results for the industry using the existing agricultural land base. Finally, these results should be viewed as caricatures of the systems they represent, not as definitive projections of the future. They provide a rough approximation of how researchers believe the system behaves. Nevertheless, they are quite informative as to the basic tendencies and pressures faced by a nascent biofuels industry, and suggest that without significant economic intervention and technological breakthroughs, growth of the industry may continue to lag behind expectations.

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