

## Biofuels: Network Analysis of the Literature Reveals Key Environmental and Economic Unknowns

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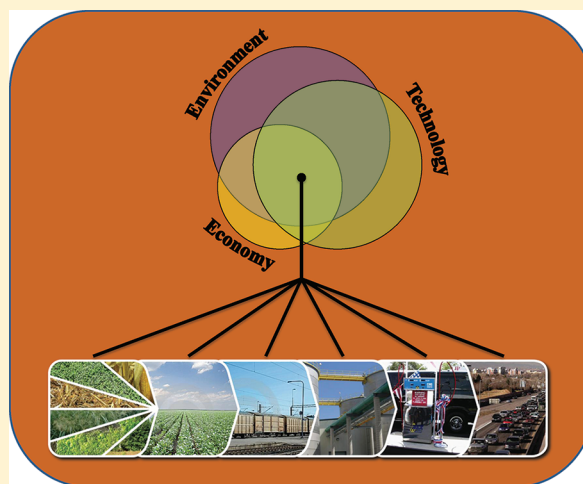
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### Supporting Information

**ABSTRACT:** Despite rapid growth in biofuel production worldwide, it is uncertain whether decision-makers possess sufficient information to fully evaluate the impacts of the industry and avoid unintended consequences. Doing so requires rigorous peer-reviewed data and analyses across the entire range of direct and indirect effects. To assess the coverage of scientific research, we analyzed over 1600 peer-reviewed articles published between 2000 and 2009 that addressed 23 biofuels-related topics within four thematic areas: environment and human well-being, economics, technology, and geography. Greenhouse gases, fuel production, and feedstock production were well-represented in the literature, while trade, biodiversity, and human health were not. Gaps were especially striking across topics in the Southern Hemisphere, where the greatest potential socio-economic benefits, as well as environmental damages, may co-occur. There was strong asymmetry in the connectedness of research topics; greenhouse gases articles were twice as often connected to other topics as biodiversity articles. This could undermine the ability of scientific and economic analyses to adequately evaluate impacts and avoid significant unintended consequences. At the least, our review suggests caution in this developing industry and the need to pursue more interdisciplinary research to assess complex trade-offs and feedbacks inherent to an industry with wide-reaching potential impacts.



### ■ INTRODUCTION

Over the last ten years, biomass-based liquid transportation fuels, known collectively as “biofuels,” have increasingly become part of the world’s planned energy mix. In the United States, 36 billion gallons of biofuels are slated to be in use by 2022, which will represent approximately 11% of the country’s transportation fuel demand. (Based on transportation fuel estimate by U.S. Energy Information Administration 2010 Annual Energy Outlook reference case projection, see Table 2 ([http://www.eia.gov/oiaf/archive/aeo10/aeoref\\_tab.html](http://www.eia.gov/oiaf/archive/aeo10/aeoref_tab.html)). This assumes that 36 billion gallons will consist of 31 and 5 billion gallons of ethanol and biodiesel, respectively, and adjusts energy content of both fuels relative to gasoline.) Ten percent of the fuel consumed for transportation by 2020 must be from renewable sources in the European Union, while Brazil retains a long-standing 20–25% ethanol mandate.<sup>1</sup>

Biofuels are commonly touted as a dual solution to the problems of dependence on foreign energy sources and climate change, but their impacts are not confined to these two areas. Energy production and use is one of the most intensive human

enterprises, with numerous economic and societal benefits, as well as societal and environmental drawbacks. Any policy that seeks to significantly alter the form and method of energy exploitation raises the specter of unintended or misjudged consequences. The goal of greenhouse gas (GHG) savings was challenged after indirect land use change, resulting from displaced food and feed production, was included in the estimation of emissions.<sup>2</sup> Though estimates of indirect land use change attributed to biofuels policies continue to be debated in the literature,<sup>3</sup> such attention to the unintended consequences of biofuel production and use has stimulated discussion of other potential economic, social, and environmental impacts, including effects on food security, environmental justice, and biodiversity conservation.<sup>4</sup> Many international groups are now proposing to measure, track, and rank forms of renewable

Received: July 13, 2011

Revised: October 21, 2011

Accepted: December 7, 2011

Published: January 9, 2012

**Table 1. Total Number of Articles Retrieved for Themes and Number and Percentage of Articles Retrieved for Topics within Themes<sup>a</sup>**

Theme	Topic	Example keywords	Number of articles (adjusted)	Percentage of articles within a theme
Environment and Human Well-being			887	
	Greenhouse gases (GHG's)	carbon dioxide, emissions	313	35%
	Water resources	water, effluent	268	30
	Land use/land change (LULC)	habitat, forest	210	24
	Food security	food, grain crop	202	23
	Soil resources	soil, erosion	152	17
	Air quality (non-GHG's)	particulate matter, carbon monoxide	138	16
	Biodiversity	wildlife, richness	80	9
Production-Distribution Technology and Infrastructure	Human health	asthma, cancer	15	2
			781	
	Fuel production	hydrolysis, fermentation	516	66
	Feedstock production/agronomics	tillage, intensification	301	39
	Fuel distribution and infrastructure	pipeline, storage tank	130	17
Economy	Feedstock logistics	harvest, felling	93	12
			430	
	Costs of production	investment, labor	258	60
	Policy	legislation, subsidy	220	51
	Market forces	price, supply and demand	145	34
Geography	Trade	import, export	34	8
			454	
	Asia	China, Korea	161	35
	North and Latin America	United States, Mexico	154	34
	Europe	Germany, Sweden	83	18
	South America	Brazil, Argentina	73	16
	Africa	Egypt, Kenya	46	10
	Oceania	Australia, New Zealand	10	2

<sup>a</sup>Number of articles has been adjusted by a relevancy ratio as described in the text. Percentages add up to more than 100% because some articles address more than one topic.

energy, including but not limited to biofuels, based on their ability to meet environmental criteria that may not have been previously considered.<sup>5</sup>

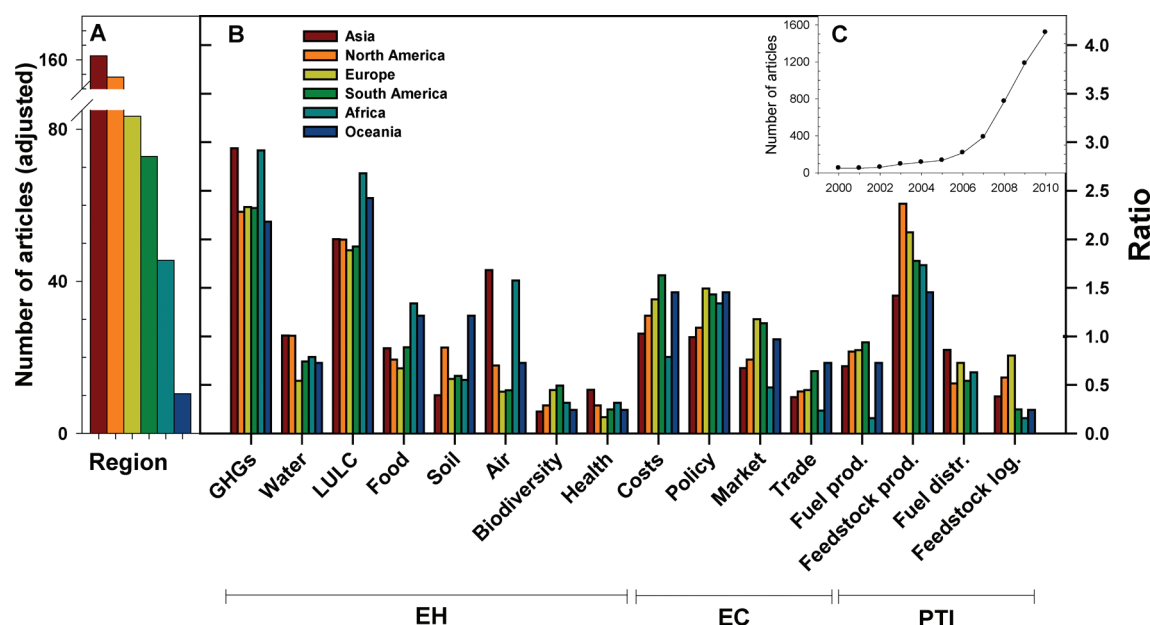
The capability of decision-makers to evaluate the total impacts of biofuels, including their environmental and economic trade-offs, and the accuracy of those evaluations depend on the availability of robust data and analyses. Here, we ask: does the published, peer-reviewed literature present a full portrait of biofuels and their potential impacts and trade-offs? Confidence in incipient policies governing biofuels that aspire to be environmentally, economically, and socially conscious, would be enhanced by an affirmative finding.

To answer the above question, we analyzed 1622 biofuels-related articles published between 2000 and 2009 across a range of social, environmental, and technical topics. We also examined geographic trends. Finally, we examined the frequency of interdisciplinary research as an index of our understanding of the complex interactions and feedbacks possible under global biofuel production scenarios. Such an approach has previously been used to visualize connections between concepts in the scientific literature and to identify logical gaps in study.<sup>6</sup> We did not attempt to review the specific findings of the literature. Rather, our primary goal was to ascertain the structure of biofuels research efforts in the past decade in order to stimulate discussion of its utility to a range of stakeholders.

## METHODS

**Defining Areas of Research and Keyword Selection and Vetting.** We first defined three major areas of research (termed “themes” hereafter): environment and human well-being (EH), economics (EC), and production-distribution technology and infrastructure (PTI). We subdivided themes into more specific “topics” that became our units of analysis (Table 1). We also included geography as a fourth theme, to assess the degree to which other topics had been discussed in different regional contexts around the world.

For each of the topics, we generated an initial set of search terms, or keywords, utilizing both our own knowledge of the biofuels research field and the knowledge of a group of elicited experts. Generating search terms *a priori* rather than deriving them from the literature allowed us to describe patterns in expert-identified, emerging topics in biofuels research in addition to established topics, as well as the relationships between them.<sup>6</sup> We put the keywords through an objective two-step vetting process using ISI Web of Knowledge to ensure their appropriateness/specificity (defined generally as whether the keyword pertained unambiguously to biofuels in the context of liquid transportation fuels), and redundancy (defined as whether the keyword failed to access a unique subset of the literature). We searched “biofuel\* AND keyword”, selected 10 articles at random from the search output, and read the



**Figure 1.** Biofuels publishing trends by geographic region, topic and year. (A) Total numbers of articles retrieved per region. (B) Ratio of the number of articles per topic for a region to the average number of articles per topic for that region. Topics are grouped by thematic areas. EH = Environment and Human Well-being, PTI = Production-Distribution Technology and Infrastructure, EC = Economy. The dotted line indicates where topical emphasis for a region is equal to the average for that region. Numbers of articles in both panels have been adjusted by a relevancy ratio as described in the text. (C) Raw number of articles retrieved per year from 2000 to 2010, unadjusted by a relevancy ratio.

abstracts. We retained the keyword if  $\geq 2$  articles were deemed relevant to the topic with which the keyword was associated. We then vetted for keyword redundancy by combining keyword searches. If the combination did not produce more results than either search individually, we only retained the keyword with more results. If the combination did produce more results, both keywords were retained. Keywords for geographic regions consisted of the name of the geographic region itself plus the names of the top 20 countries by population ( $\geq 1$  million people) in the year 2009.<sup>7</sup> One exception was Africa, where we used Zambia instead of Niger, because of ambiguity with the microbe *Aspergillus niger* used for biosynthesis of enzymes for biofuel feedstock catalysis. Our geographic search sought to describe the regions that were the subject or field location of biofuels research, not the nationality of the authors or funding bodies. A full list of keywords can be found in Supporting Information Table S1.

**Analyzing the Literature.** We used ISI Web of Knowledge (including the Science and Social Science Citation Indexes) to search peer-reviewed full-length articles and reviews, as well as shorter-form letters, published between 2000 and 2009. For each topic, we conducted a Boolean search of the keyword “biofuel\*” and the entire list of vetted keywords for that topic. For example, the search for trade consisted of: “biofuel\* AND (trade OR import OR export OR tariff)”. This process resulted in 23 individual topic searches. To examine the connectedness of literature between topics, we searched all pairwise combinations, except pairs of regions. This resulted in 216 pairwise searches.

We performed an abstract verification for article relevance. For individual topic searches, we randomly selected 20 abstracts (or all abstracts if fewer than 20 articles were retrieved) and read each to evaluate if the article was relevant to the topic. An acceptance rate was determined and multiplied by the raw number of retrieved articles to produce an “adjusted” number

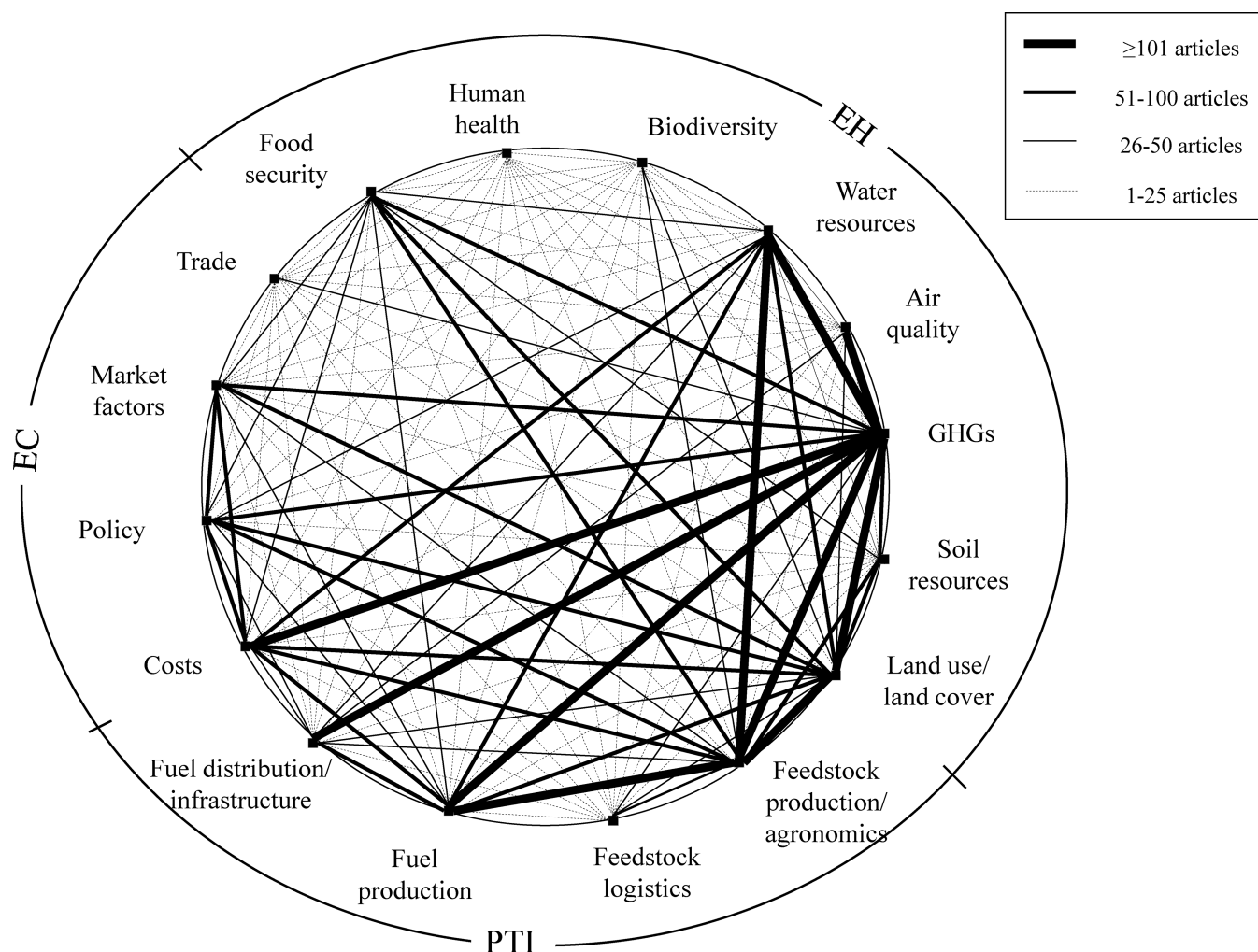
of articles. Acceptance rates ranged from 0.15 to 0.80, with an average of 0.52. For simplicity, when adjusting paired searches, we multiplied the average acceptance rate for all topics by the raw number of articles retrieved to produce the adjusted number of articles. We checked a random subsample of relevance ratios for topic-pairs and found no systematic trends or bias.

**Constructing the Network Diagram.** We constructed a network diagram as in Vanderhoeven et al.<sup>6</sup> Briefly, we arranged all of our topical areas, except for regions, as nodes on the perimeter of a circle. Lines, or edges, connecting nodes were drawn between all topics where we found evidence for literature that addressed both. Line thickness was adjusted to categorically reflect the number of articles that addressed a given pair of topics.

## RESULTS

**Research Themes and Topics.** We found a wide range of research activity on the themes and topics examined in this analysis (Table 1). The number of peer-reviewed articles addressing the economic (EC) aspects of biofuels was approximately half that of either environment and human well-being (EH) or production-distribution technology and infrastructure (PTI) articles. The most common topics in the literature were fuel production technologies, GHG emissions, and feedstock production/agronomics, each with over 300 articles. The least studied topics, excluding geographical categories, were human health, trade, and biodiversity, which retrieved 129 articles combined. Human health and trade, in particular, were represented by a very limited number of articles (15 and 34, respectively).

Analyses by region revealed substantial heterogeneity in total research effort and in topical emphasis. Overall, Asia and North/Latin America received the most attention in the literature, Oceania and Africa the least, and South America and



**Figure 2.** Network diagram showing the number of articles in common between all pairs of topics in the analysis except geographic regions. Topics are grouped by thematic areas. EH = Environment and Human Well-being, PTI = Production-Distribution Technology and Infrastructure, and EC = Economy. Numbers of articles have been adjusted by a relevancy ratio as described in the text. Line thickness indicates the categorical strength of the connection between topics.

Europe received intermediate attention (Table 1, Figure 1A). We also calculated the relative effort per topic for each geographic area to get a picture of the differing emphases between regions. This was calculated as the ratio of the number of adjusted articles in a particular topic within a region over the average for all topics within that region. GHG's, land use/land change (LULC), and feedstock production had strong representation in the literature across regions, while other topics, including biodiversity and human health, showed consistent lack of literature across regions (Figure 1B). Certain topics, however, showed a greater interaction with geography. The number of water resources articles was equal to the average for Asia and North/Latin America, and was comparatively underrepresented for the rest of the world, Europe in particular. Articles on food security were above average for Africa and Oceania, and below average for all other regions. Soil resources research was below average in all regions except Oceania. Air quality showed some of the largest differences among regions, overrepresented in Asia and Africa (though low in total effort in the latter) and underrepresented elsewhere. There were few studies in Africa, an already understudied region, on the trade and market potential for biofuels.

**Interdisciplinary Research.** Our network analysis revealed strong asymmetry in the connectedness of different research topics in the biofuels literature. Among the 23 topics we examined, GHG emissions was the most well-connected, sharing at least 50 articles with 11 other topics (Figure 2). Land use/land cover, feedstock production/agronomics, fuel production technology, and costs of production were also well-connected to other topics, including topics outside of their respective thematic areas. Not surprisingly, the same topics with the fewest numbers of articles were also the most isolated. Human health, trade, biodiversity, and feedstock logistics tended to be loosely associated or unassociated with articles in other disciplines. Noticeably scarce were studies on how economic policy, market factors, and trade might influence how biodiversity is impacted by biofuels. Although the lack of connections appeared to be a function of the small number of articles in the case of human health and trade, it was not exclusively so for biodiversity. Averaging the proportion of articles connected to each topic, biodiversity articles addressed another topic only 15% of the time versus, for example, 27% of the time for GHG articles.



## ■ DISCUSSION

Our analysis reveals substantial heterogeneity in the amount of research on the numerous critical topics relevant to an industry with as wide-reaching effects as biofuels. This holds for individual topical areas and geographic regions, as well as for cross-topic linkages. It is debatable whether this asymmetry is appropriate and whether the current body of literature is mature enough to effectively support the informed development of this international industry; or whether the research gaps we have identified indicate substantial risk of unanticipated, unintended consequences. In either case, we argue that there is enough uncertainty to warrant caution, especially in several understudied topics and regions.

The paucity of studies addressing human health, trade, and biodiversity has several implications. With the escalation of biofuel production and use locally and globally, a renewed examination of risks and hazards for human populations facing chemical exposures is certainly warranted. The U.S. Environmental Protection Agency's Regulatory Impact Analysis of the 2007 revised Renewable Fuel Standard program found that increasing biofuel production and use would lead to increases in particulate matter and ozone, leading to net negative impacts on several measures of human health.<sup>8</sup> Exposure of humans to chemicals via other routes, including surface water and groundwater, were not assessed in the aforementioned analysis. Additionally, trade and trade policy will play an increasingly important role in how and where feedstocks and biofuels are produced worldwide. In 2007, approximately 27% of Europe's mandated renewable transportation fuel use was being met by imported biodiesel and ethanol.<sup>7</sup> Meanwhile, the U.S. continues to promote domestic production through the use of import tariffs on ethanol from countries like Brazil. The elimination of this tariff could increase ethanol imports to the U.S. in 2015 by as much as 87% over projected volumes under current policies.<sup>9</sup> Of note, such a change in trade policy coupled with the elimination of the ethanol tax credit passed in the U.S. Senate in the summer of 2011.

Finally, large-scale production and use of biofuels is likely to modify several of the stressors that already threaten regional biodiversity, including land use change, climate change, air pollution, and biological invasions, e.g., refs 10a–c. Despite recognition of this in some scientific circles, only 80 articles were retrieved in our search. A lack of research on the effect of biofuels on biodiversity was also identified by a recent report by the National Research Council.<sup>11</sup> To put this into context, a similar ISI search using "biodiversity" AND "climate change" yielded many more retrieved articles: 2657 published between 2000 and 2009. Regionally, the same pattern holds; adding South America or Asia keywords to the above biodiversity-climate change search yielded 95 and 141 articles, respectively—easily surpassing the 5 (South America) and 6 (Asia) articles at the nexus of biofuels, biodiversity, and these regions. Though the number of climate change–biodiversity articles was not adjusted per our analysis, they nevertheless exceed those of biofuels by over an order of magnitude. Our results strongly imply that empirical data or modeling efforts on the effects of biofuels, explicitly using biodiversity as a dependent variable, are sorely needed. The need may be greatest in countries such as Brazil, Indonesia, and Malaysia, which contain biodiversity hotspots of global importance<sup>12</sup> and are already centers of biofuel production.

An under-representation of developing regions in the biofuels literature was found across topic areas. This raises questions about impacts of the industry in places where large-scale development of biofuels could either reap great rewards if done sustainably, or lead to widespread environmental degradation if done irresponsibly. Exploring the data set further, we also found a country bias within these regions. For instance, roughly 95% of the Asia articles were from China and India, almost 80% of the South America articles exclusively addressed Brazil, and roughly 75% of the North America/Latin America articles focused on the U.S. Thus, vast areas of the world remain virtually unstudied, potentially creating lags to implementation of international monitoring and standards for sustainable biofuel development.

Furthermore, our analysis of topics according to region revealed some important geographic gaps in research effort. Erosion in Asia has long been an environmental problem, in particular from the vast agricultural regions of the Loess Plateau in China covering over 600,000 km<sup>2</sup>,<sup>13</sup> yet little attention has been paid to examining how biofuels production may impact this sensitive area. Surprisingly, market factors and trade were just as underrepresented in Asia (mostly China) as they were in North/Latin America (mostly U.S.). For Europe, many of the economic topics were well-represented, perhaps at the expense of important environmental topics such as water resources which have recently been of intense interest for biofuel feedstocks such as Giant Miscanthus.<sup>14</sup> Such trends do not necessarily point to problems in the distribution of literature within regions, but the patterns are worth discussion in the context of the needs of decision-makers and stakeholders in different parts of the world.

Increasingly, organizations and governments are relying on systems approaches to understand the consequences of particular policy decisions. These are often interdisciplinary analyses to try and capture the complexities and feedbacks associated with increasing biofuel production, across the stages of the production chain, for multiple environmental and economic impact domains and from local to global scales. Common approaches include life cycle analyses (LCAs),<sup>15</sup> and general and partial equilibrium models (e.g., Global Trade Analysis Project [GTAP] and others<sup>16</sup>). Although promising, these approaches are often hampered by the large amounts of input data required, as well as fundamental uncertainties in model processes such as market elasticities and local land management practices. We found that some topics such as GHG emissions and land use/land cover are commonly discussed in an interdisciplinary fashion. Whether this is in a substantive enough way to inform modeling efforts and/or policy decisions remains unanswered. On the other hand, many topics appeared relatively isolated, clouding the prospects for an integrated analysis on the impacts of biofuel production across multiple nations.

We acknowledge several important caveats to our analysis. First, we describe trends only for recent peer-reviewed literature from journals indexed by ISI Web of Knowledge. Clearly, research published before 2000 or after 2009 and in the gray literature such as in government and industry reports will also be important to understanding the impacts of biofuels. And while use of additional online databases of peer-review research might have augmented the literature in our analysis, over the last five years, Thompson Reuters has greatly expanded and evened their indexing of high-quality social science and international journals (Testa, J. 2011. The globalization of

Web of Science: 2005–2010. [http://wokinfo.com/products\\_tools/multidisciplinary/webofscience/contentexpansionessay/](http://wokinfo.com/products_tools/multidisciplinary/webofscience/contentexpansionessay/)). Thus, use of other databases could have altered our results, though likely not substantially given the broad journal coverage of the ISI Web of Knowledge. Furthermore, it is unlikely that this literature-based approach captures all the relevant information on research effort; it could be augmented with other approaches such as interviews and tracking grants awarded by governmental and nongovernmental institutions, among others. We also note that biofuels research is a rapidly expanding field that may be only beginning to show signs of slowing (Figure 1C). Second, we had no expectation that the categories representing our topics of interest would be equally covered or connected in the literature. This is because some categories may be inherently broader (for example, water resources versus the narrower feedstock logistics), more important, or overlap more than others. However, our approach for a network analysis on *a priori* selected keywords and the visualization of connections between topics in the literature is a procedure that has been used many times in social, ecological, and computer sciences<sup>6,17</sup> and is rooted in the mathematical and physical domains of network theory.<sup>18</sup> Despite the methodological and epistemological limitations of our approach, we hope this assessment will provide direction to the research community toward understudied topics and regions, and stimulate greater integration of often disparate fields.

Agriculture is already the most intensive land use globally, comprising over a third of the global land area (<http://faostat.fao.org/site/291/default.aspx>) and 70% of freshwater use,<sup>19</sup> while contributing to massive changes in earth's biogeochemical cycles.<sup>20</sup> Biofuels have the capacity to alter global land use patterns, underscoring the importance of augmenting understudied areas and topics in this rapidly developing industry. The optimal mix of scientific effort to support its sustainable development is unknown, and likely depends on several objective and subjective criteria. For instance, industrialized nations have more often emphasized understanding the environmental consequences of biofuel production and use, while several countries in Africa and international bodies have prioritized food security or socio-economic impacts.<sup>5</sup> Thus, the data and analysis needs vary from place to place. Our intent is, by exposing the structure of recent biofuels research efforts, to raise awareness about scientific and economic areas still relatively unexplored and promote the discussion of their applicability to a range of stakeholders. Such an approach increases the likelihood of accurately anticipating the direct and indirect impacts of biofuels policies, while reducing the impacts of unintended consequences.

## ■ ASSOCIATED CONTENT

### ● Supporting Information

Table S1. This information is available free of charge via the Internet at <http://pubs.acs.org/>.

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## ■ ACKNOWLEDGMENTS

We thank early contributors to this study A. Chen and R. Simmons. We also kindly acknowledge three anonymous

reviewers for their thoughtful critique of an earlier version. This manuscript represents views of the authors only and not official views of the Environmental Protection Agency.

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