sustainability

MDPI

Article

A Regional Analysis of the Life Cycle Environmental and Economic Tradeoffs of Different Economic Growth Paths

Weiwei Mo *, Darline Balen, Marianna Moura and Kevin H. Gardner

Department of Civil and Environmental Engineering, University of New Hampshire, Durham, NH 03824, USA; darlinebalen1@gmail.com (D.B.); marianna.omoura@gmail.com (M.M.); kevin.gardner@unh.edu (K.H.G.)
* Correspondence: Weiwei.mo@unh.edu; Tel.: +1-603-862-2808

Received: 12 December 2017; Accepted: 12 February 2018; Published: 18 February 2018

Abstract: Different economic development strategies may result in varied socioeconomic and environmental synergies or tradeoffs, suggesting an opportunity for environmentally conscious planning. To understand such synergies or tradeoffs, a dynamic environmental life cycle assessment was conducted for eleven groups of New Hampshire industries. Historical state level Gross Domestic Product (GDP)-by-industry data was combined with economic input-output analysis to calculate the direct and life cycle energy use, freshwater use, greenhouse gas emissions, and eutrophication potential of each industry on a yearly basis for the period of 1997–2012. The future development of agriculture, traditional manufacturing, high tech, and tourism industries were investigated based on government projections. Total life cycle impacts of the 11 industries were found to represent around three to seven times those of direct impacts, indicating the significance of the supply chain impacts. Traditional manufacturing has the highest life cycle impacts even though it contributes to less than 10% of the state GDP. Future development of high tech was found to be the best strategy to increase GDP while imposing the least additional environmental impacts. Tourism presents relatively high impacts in terms of freshwater use and eutrophication potential, and a change in recreational style might be able to reduce its impacts.

Keywords: economic development; industrial GDP; state-level economic planning; economic input-output life cycle assessment; energy and greenhouse gas emissions; freshwater use

1. Introduction

Human well-being and the prosperity of our society are increasingly being challenged by the limited ecological capacity and resources as the population and consumption grow nationally and globally [1,2]. According to the Millennium Ecosystem Assessment, over 60% of the 24 types of ecosystem services identified are being degraded or used unsustainably [3–5]. Poor communities are often the most vulnerable to environmental degradation, which further challenges environmental justice and sustainability [3,6,7]. It has been argued that decoupling growth in dollars from growth in resource consumption and environmental impacts might be the only path to “true” sustainability [8,9]. Attaining such a goal requires a comprehensive understanding of the tradeoffs between economic growth paths and various environmental impacts to inform future environmentally conscious planning and resource conservation [4,10].

Industries are the primary force of economic growth by providing a variety of economic functions in terms of employment opportunities, personal income, corporate profits, and government spending [11]. Nevertheless, they also generate varied levels and types of environmental impacts, which feedback to and influence the well-being of socioeconomic systems. Industrial environmental impacts have been previously assessed through approaches such as biophysical process-based modeling [12–15], material and energy flow analyses [16–20], monetary valuation methods (e.g., willingness-to-pay, willingness-to-accept etc.) [21–24], and life cycle assessment [25–28]. Among them, biophysical process-based modeling, material and energy flow analyses, and monetary valuation methods are primarily focused on quantifying the direct or relatively short supply chains' emissions and/or benefits of an industrial entity, while the indirect impacts associated with the upstream supply chains are often neglected or insufficiently described. This could potentially result in an underestimation of the actual industrial impacts [29] and biased outcomes when comparing different economic development paths. Life cycle assessment (LCA), on the other hand, measures the cradle-to-grave or cradle-to-cradle impacts of products, systems, or processes [30], which enables the elimination of sub-optimization and shift of environmental burdens among different life cycle stages or environmental media [31,32].

Although LCAs have been widely applied in assessing technologies and systems, only a few applications have been made in comparing regional economic development paths to guide future planning and management [33–38]. The regional scale in this study is defined as a scale beneath the national level, but above the local or municipal scale [36]. The difficulty of carrying out regional assessments lies in the intensive data and information required by the traditional process-based LCA. Process-based LCA largely depends on detailed inventory data collected from each industrial entity and each process in the supply chains. Hence, the process-based LCA often suffers from an incomplete system boundary as decisions have to be made whether to include processes or not [25,39]. The economic input-output life cycle assessment (EIO-LCA) is another method which investigates monetary transactions among all industries in an economy to trace both direct and indirect resource requirements and emissions from a certain industry [40–43]. The EIO-LCA offers a more comprehensive and comparable system boundary for each industry, and it is suitable for estimating the macro-scale environmental impacts of industries without having to obtain details from each industrial entity. Particularly, the U.S. Bureau of Economic Analysis (BEA) has been providing historical economic input-output (IO) tables to the public for more than 30 years (an industrial classification switch took place in 1997), which could be utilized to gain insights into dynamic changes of environmental impacts associated with economic growth and industrial compositions [44]. Therefore, EIO-LCA is utilized in the current study for investigating the environmental tradeoffs of different economic development scenarios in the state of New Hampshire (NH).

One critical step in LCA is defining the functional unit. To enable the comparison among industries, as well as to evaluate the environmental and economic tradeoffs, we define the functional unit as the generation of $1 of Gross Domestic Product (GDP). The final results are expressed in a form similar to the concept of eco-efficiency, which describes the efficiency of ecological resources being used to meet human needs [45]. It is measured as the ratio between the added economic value of products or services and their associated (added) environmental influences [46–50]. In this study, a cradle-to-gate approach will be adopted instead of the gate-to-gate approach used in estimating eco-efficiency, where only the consumptions and emissions generated strictly within the boundary of a particular industry or industrial establishment are accounted [47,51].

This study aims to systematically evaluate the environmental and economic tradeoffs of the four most-debated economic growth paths (discussed in detail in Section 2) in NH from a life cycle perspective. Specifically, an EIO-LCA was performed utilizing the state-level and national-level economic IO accounts. The calculated life cycle impacts were normalized to a GDP basis for comparison purposes. Future scenarios of NH economic development were generated based on NH governmental predictions and the environmental and socioeconomic tradeoffs among these scenarios were examined. This study provides an important environmental perspective which is often neglected in the decision-making of governmental interventions on economic growth (tax credits, subsidies, etc.) [52]. Results from this study could support the identification of a path that could potentially lead to the highest GDP growth and lower resource consumption and emission.

2. Study Background and Motivation

New Hampshire is one of the smallest states in the U.S. with a population of 1.3 million and a land area of around nine thousand square miles [53]. Nevertheless, it has a population density around twice the national average and a median household income around 22% above the national average [53]. While the state actively seeks continuous economic growth in general, economic well-being is not even across the state. The northern third of the state suffers from high poverty rates, which indicates a need to further strengthen economic development in the region. Currently, services, finance, and trading industries dominate the NH economy (Figure 1). Traditional manufacturing, as well as high technology (or high tech) (computer and software industries), industries also represent a significant proportion of the state's GDP and have been steadily growing. The state also has abundant forestry and recreational resources supporting its tourism and construction industries. Detailed economic sectors that are included in each of the industrial categories listed in Figure 1 are provided in Table S1.

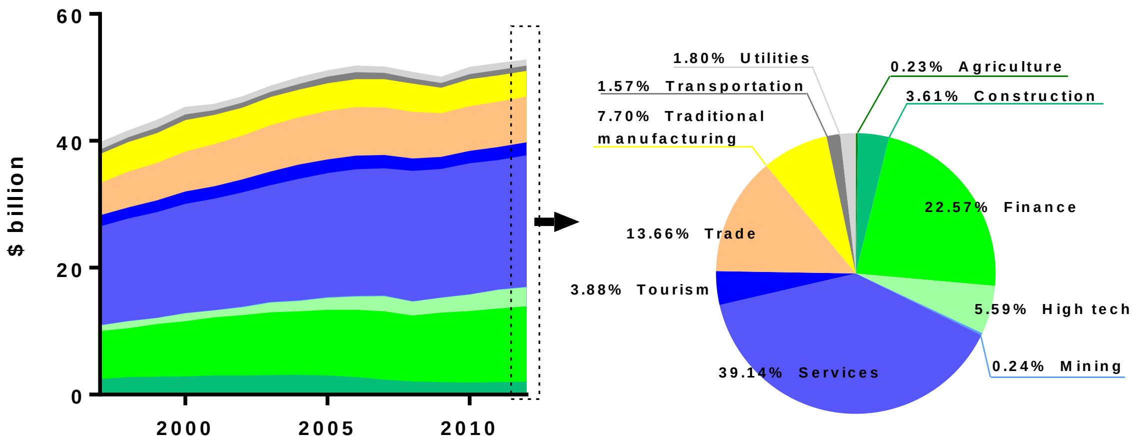

Figure 1. Percentage contributions of varied industries to New Hampshire's Gross Domestic Product from 1997 to 2012 (**left** panel) and in 2012 [54] (**right** panel).

Four types of future economic growth paths have been widely debated in the state, in which agriculture, tourism, high tech, or traditional manufacturing will be encouraged to grow, respectively. Backgrounds of these debates are detailed as follows:

- Agriculture: In the 1800s, NH was largely deforested driven by population growth and the explosion of wool demand. Forest was, at a point, reduced to less than 50% of the land area as compared to around 84% forested land currently [55,56]. There has recently been a return of this trend in increasing farm land in the state. For instance, recent movements related to local food production responding to the increased concern over food security are garnering significant attention, with the New England Food Vision calling for significant increases in arable land in NH over the next 40 years [56].
- Tourism: Tourism, although comprising a relatively small historical GDP contribution to the NH economy (3.88% in 2012), has always been considered an important industry in NH. New Hampshire attracts tourists during summer seasons for activities such as beach recreation, hiking, and camping, and during winter seasons for activities such as skiing and skating. Tourism, which is traditionally viewed as a relatively low impact industry, is expected to further increase according to the projection by the NH government.
- High tech: Industrial output of the high-tech industry has been growing steadily in NH, even during the most recent economic recession in 2009. The sector is viewed as a powerful engine of economic growth in NH, not only because of its excellent capability in generating GDP, but also because it employs one sixth of the state's private sector workers.
- Traditional manufacturing: Traditional manufacturing has declined significantly over the past half century, along with a general trend in the US of relocating factories overseas for reduced production costs. Although the declining pace has greatly reduced over the past two decades,

this declining trend is projected to continue in NH. Nevertheless, concerns have been raised over losses of employment opportunities and slower recovery from economic recession caused by such relocation. An ongoing debate asks for a consideration and assessment of the regrowth of traditional manufacturing.

The current debates are mainly centered on the abilities of different industries to import wealth from outside of the state and to provide job opportunities, whereas the potential tradeoffs in terms of economic growth and the natural environment degradation (e.g., pollution, resource depletion) have not been discussed. This could potentially lead to the overexploitation of natural resources and ecosystem services, resulting in long term degradation of the well-being of the local population, as well as escalation of environmental costs. For example, elevated cyanobacteria levels due to water pollution have resulted in increased beach closure days and human infections for many NH beaches [57], which may lead to economic losses in the tourism industry. Industrial greenhouse gas (GHG) emissions and the resulting climate change (a warmer and wetter climate predicted for NH [58]) could seriously influence the state's ski industry, forests, coasts, foliage, fishing, and human health [59,60], as well as impose social costs in administering and implementing pertinent policies and regulations such as the Regional Greenhouse Gas Initiative (RGGI) [61].

3. Materials and Methods

3.1. Economic Input-Output Life Cycle Assessment

Given that NH's economy and industrial composition vary over time, an EIO-LCA was performed in the current study to understand historical and future environmental impacts associated with varied NH economic sectors. NH real industrial GDP in chained 2009 dollars were obtained from the state-level GDP-by-industry accounts provided by the BEA for the years 1997 to 2012. According to the BEA, an industry's GDP is measured by its value added, which is equal to its gross output (total industrial output) minus its intermediate purchases from domestic industries or from foreign sources (industrial intermediate output), which are consistent with the annual economic IO accounts [44]. GDP values for a total of 90 NH industrial sectors classified based on the North American Industry Classification System (NAICS) were obtained [44]. Out of these 90 industrial sectors, 50 non-overlapping sub-sectors that partition the entire NH economy were identified and used for the subsequent analyses (Table S1 of the supplementary information (SI)). They were then converted to total industrial outputs based on the ratios between total industrial outputs and industrial GDPs obtained from annual national economic IO tables (producer's prices). This assumes that the ratios between the total industrial output and the GDP are similar at the national and state levels, meaning the industrial entities that reside within NH are on average similar to or typical of the ones across the country in terms of inter-industrial demands, employee compensation, and operation surplus, etc., for producing \$1 of products. These annual total industrial outputs in chained 2009 dollars were further converted to 2002 dollars using the Consumer Price Indexes of the years 2002 and 2009 obtained from the U.S. Bureau of Labor Statistics [62]. Equation 1 provides a combined formula for the two conversion steps in estimating sectoral industrial outputs.

$$O_{i,t}^{2002} = GDP_{i,t}^{2009} \times \frac{NO_{i,t}}{NGDP_{i,t}} \times \frac{CPI_i^{2002}}{CPI_i^{2009}} \quad (1)$$

where,

$O_{i,t}^{2002}$ = the total industrial output of industry "i" in year "t" reported in 2002 dollars, million \$;

$GDP_{i,t}^{2009}$ = the NH GDP of industry "i" in year "t" reported in 2009 dollars obtained from the state-level GDP-by-industry accounts, million \$;

$NO_{i,t}$ = the national total industrial output of industry "i" in year "t" obtained from the annual national economic IO accounts in year "t", million \$;

$NGDP_{i,t}$ = the national GDP of industry "i" in year "t" obtained from the annual national economic IO accounts in year "t", million \$;

CPI_i^{2002} = the Consumer Price Index of industry "i" in year 2002;

CPI_i^{2009} = the Consumer Price Index of industry "i" in year 2009;

i = the industry index; and;

t = the year index, any year between 1997 and 2012.

The converted total industrial outputs were further used to analyze five types of environmental impacts associated with each industry: life cycle energy, greenhouse gas emissions, freshwater eutrophication, marine eutrophication, and freshwater uses. The aforementioned life cycle environmental impacts associated with one million dollars of industrial output were obtained from the U.S. 2002 benchmark IO database embedded in SimaPro 8.0 (PRé Sustainability, Amersfoort, Netherlands). This database has been widely applied in many previous LCA studies [63,64] and is the most current database available with environmental extensions [41,65]. A previous study of the U.S. economic structure has found its change over a period of 24 years to be incremental [66]. Utilizing the impact characterization methods embedded in SimaPro also produces comparability with previous process-based LCAs. The "Cumulative Energy Demand" method was used to estimate the life cycle energy associated with each industry [67]. The "IPCC 2007 GWP 20a" method was utilized to calculate the life cycle GHG emissions of each industry [68]. The "ReCiPe Midpoint" hierarchist version was used to quantify freshwater and marine eutrophication potentials [69]. The North American "BEES+" was used for life cycle freshwater uses approximations [70]. Equation (2) illustrates the calculations of the five-life cycle environmental impacts of a particular industrial category over the study period. Ratios between the direct and life cycle environmental impacts were estimated using the Comprehensive Environmental Data Archive 2002 (CEDA®) direct and life cycle environmental intervention tables (with system expansion and economic allocation) for each individual industry [41]. These ratios were then used to calculate the direct environmental impacts of each industrial sector. The direct and life cycle impact ratios of freshwater and marine eutrophication were arbitrarily assumed to be the same due to a lack of data. However, the model allows easy adjustment of the ratios once more data become available. All unit life cycle impacts, ratios for calculating the direct impacts, and the economic structures are assumed to remain constant for the entire study period of 1997–2012, as well as for future projections. The detailed calculations of the aforementioned steps and the ratios between direct and life cycle impacts can be found in the supporting spreadsheet titled "Calculations".

$$EI_i^n = \sum_t O_{i,t}^{2002} \times ei_{i,t}^n \tag{2}$$

where,

EI_i^n = the "n"th type of total life cycle environmental impacts of industry "i" during the study period, PJ, Tg of CO_2 eq., Mg of P eq., Mg of N eq., or GL;

$ei_{i,t}^n$ = the average "n"th type of unit life cycle environmental impacts of industry "i" in year "t", PJ/million \$, Tg of CO_2 eq./million \$, Mg of P eq./million \$, Mg of N eq./million \$, or GL/million \$; and

n = environmental impact index, life cycle energy, GHG emissions, freshwater eutrophication, marine eutrophication, or freshwater uses.

It has to be noted that the U.S. 2002 benchmark IO database includes more than 400 industrial sectors, while the GDP-by-industry accounts are much more aggregated. Hence, the pertinent industrial sectors in the U.S. 2002 benchmark IO database were first matched for each aggregated industrial sector presented in the GDP-by-industry accounts. The environmental impacts of each selected industrial sector in the U.S. 2002 benchmark IO database were estimated and then aggregated to represent each sector in the GDP-by-industry accounts. After the environmental impacts were calculated for the aggregated industrial sectors in GDP-by-industry accounts, these industrial sectors were further aggregated into 11 categories of interest, including agriculture (forestry included), construction, finance, high tech, mining, services, trade, traditional manufacturing, tourism, transportation, and utilities. The detailed industrial sectors included in the 11 categories are provided in the SI.

3.2. Economic Development Scenarios and Future Projections

To investigate the environmental and economic tradeoffs of future economic development, NH's governmental employment projections by industry and occupation were obtained and simulated for the years between 2012 and 2030 (government scenario) [71]. It was assumed that industrial GDP and intermediate outputs would change proportionally to the employment projections. Four additional scenarios were created where the growth/decline rates of agriculture, high tech, tourism, or traditional manufacturing vary individually, while all other industries maintained the same growth rates as the government scenario. Three variations were investigated for each of the four industries: 20%, 50%, and 200% of government projections. Table 1 provides the average annual industrial growth rates of the 11 aggregated industrial categories under the five future economic development scenarios.

Table 1. Average annual growth of the 11 aggregated industrial categories based on New Hampshire governmental employment projection between 2012 and 2030.

Industry	Government Scenario [71]	Agriculture Scenario	High Tech Scenario	Tourism Scenario	Traditional Manufacturing Scenario
Agriculture	0.67%	0.13%, 0.34%, 1.34%	0.67%	0.67%	0.67%
Construction	1.64%	1.64%	1.64%	1.64%	1.64%
Finance	1.04%	1.04%	1.04%	1.04%	1.04%
High Tech	0.84%	0.84%	0.17%, 0.42%, 1.68%	0.84%	0.84%
Mining	0.41%	0.41%	0.41%	0.41%	0.41%
Services	0.86%	0.86%	0.86%	0.86%	0.86%
Tourism	1.05%	1.05%	1.05%	0.21%, 0.53%, 2.10%	1.05%
Trade	0.88%	0.88%	0.88%	0.88%	0.88%
Traditional manufacturing	−0.14%	−0.14%	−0.14%	−0.14%	−0.03%, −0.07%, −0.28%
Transportation	0.27%	0.27%	0.27%	0.27%	0.27%
Utilities	−0.62%	−0.62%	−0.62%	−0.62%	−0.62%

4. Results

4.1. Historical Life Cycle Impacts of the 11 NH Industrial Categories

The historical life cycle impacts of the 11 aggregated NH industrial categories in terms of life cycle energy use, freshwater use, GHG emissions, freshwater eutrophication, and marine eutrophication during the years from 1997 to 2012 are provided in Figure 2. Figure 2 presents both direct (the first row) and total (the second row) environmental impacts of NH industries. Significant differences in terms of impact scales and industrial contributions can be observed between direct and total impacts of each type. In general, total impacts represent around 2.5–6.5 times of direct impacts when summing the values of the 11 industrial categories. This indicates the significance of the supply chain impacts, which might not occur within the state (when raw materials and semi-finished products are imported), but are embedded in the products being produced. For instance, NH imports a significant portion of its food, energy, and clothing from outside of the state [53]. On the other hand, some of the products processed or produced in NH are not eventually consumed within the state. For example, electric machinery and equipment, timber, plastics, and pharmaceutical products are among the top exported products in NH [72]. An outstanding question is the extent to which economic development planning within a state context would value supply chain vs. local environmental impacts. It also has to be noted that the sum of the total impacts by 11 industrial categories should be perceived as the maximum possible impacts because of the likelihood of double counting. For example, the environmental impacts of food production in NH are included in the agriculture category. Nevertheless, they could also be included in service industries as part of their indirect environmental impacts if locally produced food is used to provide these services. Double counting primarily results from inter-industry transactions, which ranges from around 32% of the total industrial output for the trade category up to around 62% of the total industrial output for the traditional manufacturing category (averaged value of the study period of 1997–2012). Under an extreme case of all materials and semi-products being provided from within the state, the traditional manufacturing category, for instance, could double count as much as 62% of its environmental impacts under the EIO-LCA framework. Nevertheless, given the high import rates of NH commodities from outside of the state, the double counting rates could potentially be low. Yet, it is still important to note the possibility of overestimation of the total aggregated environmental impacts. The percentages of intermediate industrial outputs out of the total industrial outputs for each industrial sector are provided in the SI.

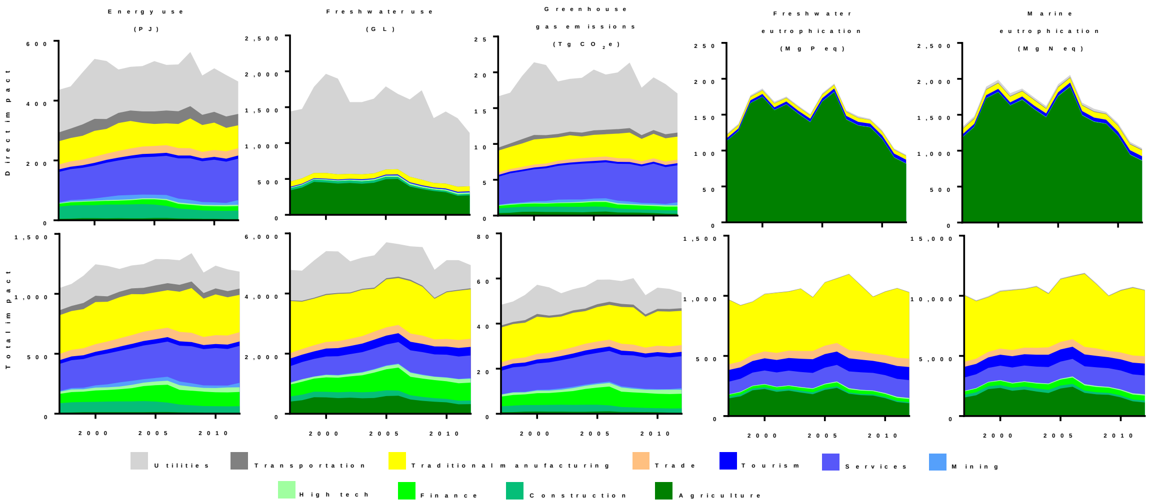

Figure 2. Direct and total impacts in terms of energy use, freshwater use, greenhouse gas emissions, freshwater eutrophication, and marine eutrophication of the eleven industrial groups in the state of New Hampshire during 1997–2012.

Traditional manufacturing is one of the largest contributors to the direct impacts in terms of energy use and GHG emissions, and it also presents the highest total impacts in terms of all five types of environmental impacts, whereas its GDP contribution is relatively small (<10%) (Figure 1). Additionally, all five environmental impacts of traditional manufacturing have some degree of temporal fluctuations, with eutrophication potentials showing the greatest fluctuation, and yet, its GDP output in the same time period is relatively stable. This demonstrates the important influences of industrial composition on the estimated environmental emissions, as they contribute in different proportions to the various impact categories. Metal products, machinery, and electronic equipment manufacturing comprise an essential proportion of traditional manufacturing in NH, and these industries are highly energy and carbon intensive. Food and beverage manufacturing and processing industries greatly contribute to the high freshwater and marine eutrophication potentials of traditional manufacturing. It is also one of the most important manufacturing industries in NH in terms of GDP. Industrial output of these food manufacturing industries also varies considerably over the study period, which has resulted in the large fluctuations of both freshwater and marine eutrophication potentials of traditional manufacturing. Traditional manufacturing is also generally water intensive. Some industries require extensively purified water for processing.

On the other hand, although finance, services, and trade industries are the largest contributors to the state GDP, their environmental impacts are relatively less significant compared with traditional manufacturing. Nevertheless, the NH services industry has relatively high direct energy uses and

GHG emissions, as well as the total impacts across all five environmental indicators compared with other industries. This is partly attributed to the direct uses of energy for space and water heating/cooling, lighting, washing, and toilet flushing. It is also partly attributed to indirect resource consumption and emissions resulting from equipment, appliances, food, and beverages purchased from other industrial sectors. Finance has relatively small direct impacts, but it has high total energy use, freshwater use, and GHG emissions. This could be explained by the high composition of the real estate industry within the finance sector, which takes into account the supply chain effects of new and re-construction. Trade has small contributions in terms of both direct and total impacts.

By the end of 2012, the GDP contribution of high tech is approaching traditional manufacturing, but its direct and total environmental impacts are much less significant compared with traditional manufacturing. This indicates a higher environmental payoff to encourage the development of high-tech industries rather than traditional manufacturing industries. The utilities category primarily includes NH water and energy utilities, and this category presents significant life cycle energy uses, GHG emissions, and water uses, while generating very little GDP. Unlike manufacturing, agriculture has high direct and total freshwater and marine eutrophication potentials and water use, which could be primarily contributed by NH's dairy and poultry farms, as well as forestry activities. Tourism also presents a high impact in terms of freshwater and marine eutrophication potentials, which can be explained by the increased supply chain demand of food and beverage services purchased by the tourism industry.

4.2. Life Cycle Impacts on Economic Basis

In order to understand the environmental and economic tradeoffs of each industry, the five total environmental impacts of each industry were normalized to impacts per $ of GDP, and ranged from the highest unit impact to the lowest. Results from the year of 2012 are presented in Figure 3. Among all 11 industrial categories, mining has the highest life cycle energy use per $ of GDP generated, while utilities present the highest GHG emissions intensity. Furthermore, the eutrophication potential and water use of the agriculture industry are much higher than other industrial categories. This is consistent with previous results reported by [34], where the water demands of agricultural sectors per dollar of industrial output are the highest among all industries. As agriculture is often a fundamental element of a state's economy, it is desirable to invest in water efficient agricultural technologies and practices to reduce its impact on water resources per generated GDP. Traditional manufacturing is always among the top four industries in all five types of environmental impacts. The utilities category is ranked the second highest industry in terms of energy use and water use, but it is among the lowest in terms of freshwater and marine eutrophication potentials. Tourism is ranked third in terms of freshwater and marine eutrophication potentials, and it is also ranked relatively high in terms of water use. On the other hand, high tech is always among the bottom four industries in terms of the five environmental impacts. The high economic but low environmental payoffs of high tech indicate that it could be a potentially viable option in further strengthening the NH economy with lower environmental trade-offs than other options.

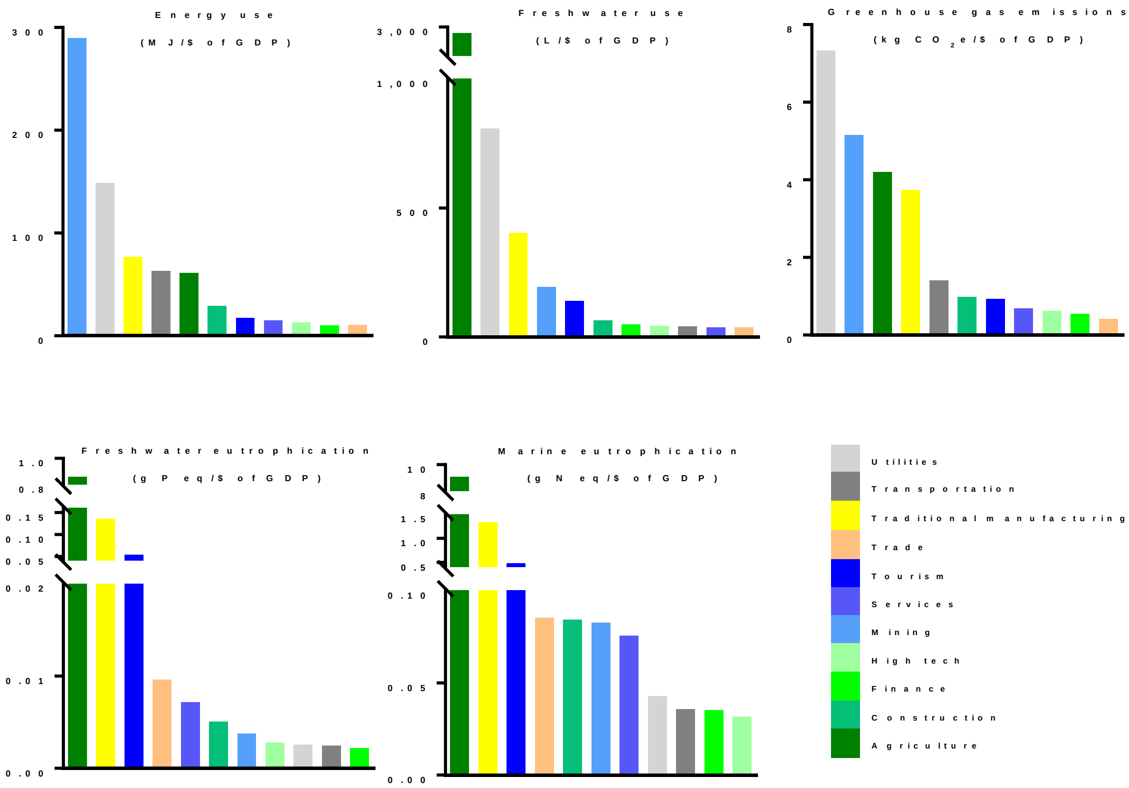

Figure 3. Life cycle energy, greenhouse gas emissions, freshwater and marine eutrophication potentials, and water use per $ of GDP for the eleven NH industrial categories in the year of 2012.

4.3. Projections of Future Life Cycle Impacts

The approximated total environmental impacts and GDP of the proposed five future development scenarios in the year 2030 are provided in Figure 4. Under the government scenario, the total life cycle energy use of the NH industries is approximately 1291 PJ and has a unit energy use of around 21 MJ/$ of GDP. The three agriculture scenarios (agriculture being 20%, 50%, and 200% of the government scenario) have very little influence on the total life cycle energy and the total GDP. Changes of high tech growth rates also have relatively low impacts on the total life cycle energy, but have substantial influences on the total GDP. The tourism scenario follows a similar trend except that it has a slightly larger influence on the life cycle energy and a slightly lower influence on the total GDP compared with the high-tech scenario. Changes in traditional manufacturing have a more significant influence on the life cycle energy. Reduction of the traditional manufacturing growth rate to the 200% of government scenario (negative growth) yields the lowest life cycle energy in 2030, but this scenario is projected to have a slightly slower GDP growth than the government scenario.

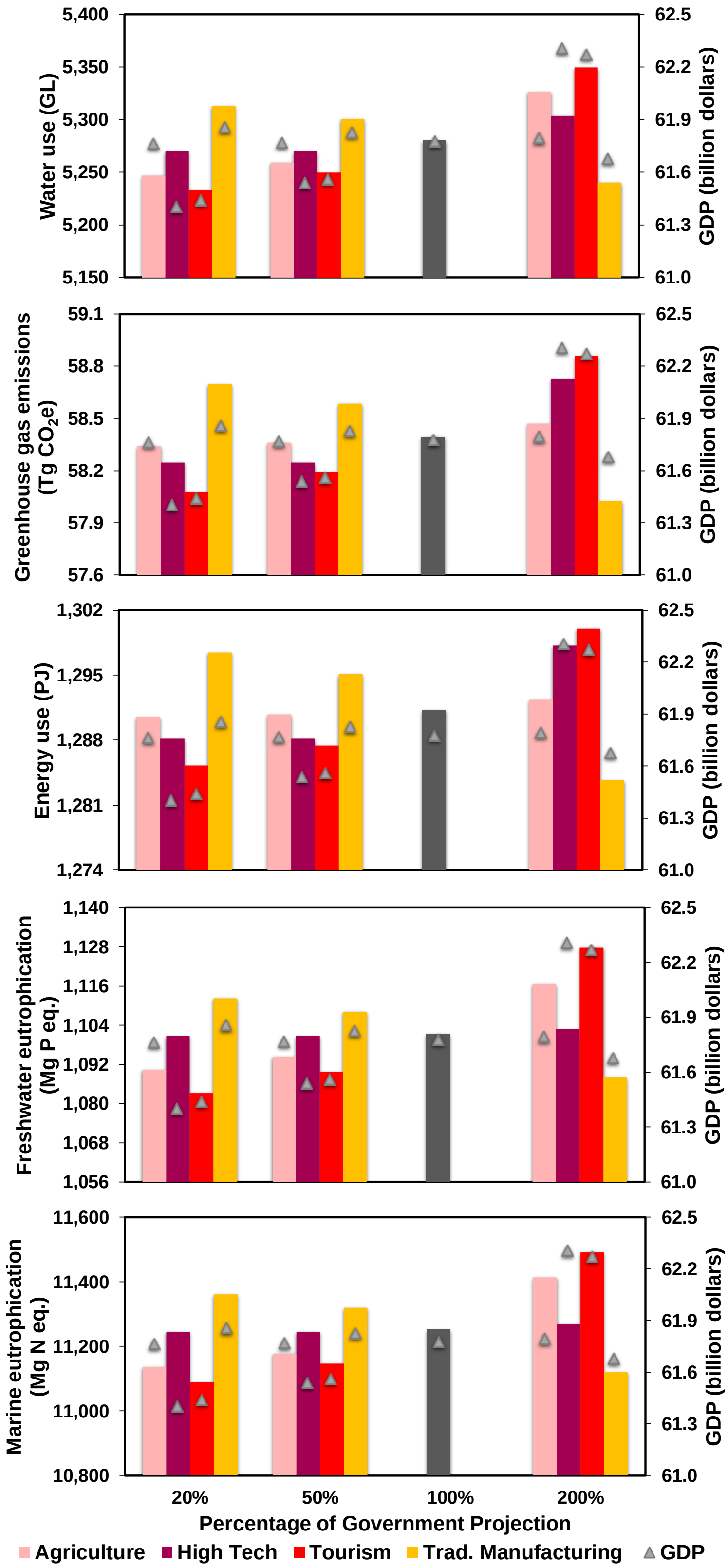

Figure 4. The greenhouse gas emissions, water and energy uses, and freshwater and marine eutrophication under 20%, 50%, and 200% of government projected growth rates of the four target industrial sectors in 2030.

In terms of GHG emissions, the government scenario projected a total GHG emission of 58.4 Tg of CO_2e (the summation of GHG emissions characterized as CO_2 equivalents) and a unit GHG intensity of 0.95 kg of CO_2e per $ of GDP. Reducing traditional manufacturing, agriculture, and tourism could slightly decrease emissions per $ of GDP. The agriculture scenario has the least influence on the total GHG emissions, followed by the high-tech scenario and the tourism scenario, subsequently. Change of traditional manufacturing growth rate has the highest influence on the total GHG emissions. Similar to life cycle energy, the reduction of the traditional manufacturing growth rate to the 200% of government scenario presents the lowest total GHG emissions in 2030.

Future projections of the proposed future scenarios in terms of freshwater eutrophication potential, marine eutrophication potential, and water use show similar trends. The government scenario projected a freshwater eutrophication potential of 1101 Mg of P eq. (18 kg of P eq./$ millions of GDP), a marine eutrophication potential of 11,252 Mg of N eq. (184 kg of N eq./$ millions of GDP), and a water use of 5280 GL (86 L/$ of GDP) in 2030. Raised tourism growth rates could greatly increase all three types of environmental impacts, followed by an increase of agriculture growth rates. Change of high tech growth rates merely influences the three types of environmental impacts. On the other hand, reductions of traditional manufacturing could substantially reduce the three types of impacts.

Overall, further reduction of traditional manufacturing presents the highest environmental benefits, yet it could potentially result in a slightly slower GDP growth. On the other hand, further raising the high-tech growth rate presents minimum additional environmental burdens and it greatly strengthens GDP growth.

4.4. Sensitivity Analysis

The sensitivity of the reported results to the uncertainties of life cycle impact intensities adopted in this study were tested. The percent changes of the estimated 2030 environmental impacts at the state level were calculated under a hypothetical 10% change of the life cycle impacts per $ of industrial output in each of the eleven industrial sectors (Table 2). For the GHG emissions and energy use, the state level results are the most sensitive to the changes in the impact intensities of the service sector. In terms of water use, freshwater eutrophication, and marine eutrophication, the reported state level results are the most sensitive to changes in the traditional manufacturing impacts. Changes of the agriculture impacts have the least influence on the state level GHG emissions and energy use. Changes of the transportation impacts have the least effect on water use. Meanwhile, mining presents the least influence on the state level freshwater and marine eutrophication potential estimations.

Table 2. Percent changes of the 2030 total greenhouse gas (GHG) emissions, water use, energy use, freshwater eutrophication, and marine eutrophication at the state level under a 10% change of the life cycle impact intensity values in each of the 11 industrial categories.

	±10% Change in the Life Cycle Impact/$ of Industrial Output				
	GHG Emissions	**Water Use**	**Energy Use**	**Freshwater Eutrophication**	**Marine Eutrophication**
Agriculture	±0.10%	±0.69%	±0.07%	±1.09%	±1.13%
Construction	±0.47%	±0.33%	±0.63%	±0.13%	±0.21%
Mining	±0.12%	±0.05%	±0.30%	±0.00%	±0.01%
Finance	±1.38%	±1.40%	±1.15%	±0.30%	±0.47%
High tech	±0.37%	±0.29%	±0.35%	±0.09%	±0.10%
Trad. manufacturing	±2.35%	±2.81%	±2.18%	±4.52%	±4.39%
Tourism	±0.41%	±0.68%	±0.35%	±1.24%	±1.09%
Transportation	±0.20%	±0.07%	±0.41%	±0.02%	±0.03%
Trade	±0.61%	±0.61%	±0.71%	±0.75%	±0.65%
Utilities	±0.94%	±1.15%	±0.87%	±0.02%	±0.03%
Services	±2.88%	±1.68%	±2.84%	±1.59%	±1.65%

5. Discussion

Traditional manufacturing provides important goods and products to the human society, yet these industries are generally water and energy intensive and have high GHG and nutrient emissions from a life cycle perspective. In NH, traditional manufacturing represents less than 10% of the state

GDP, yet it comprises more than one third of the total industrial energy and water uses and GHG emissions over the past two decades, and more than half of the estimated nutrient emissions from among the sectors analyzed. Large fluctuations of the environmental impacts associated with traditional manufacturing, despite its relatively stable GDP contribution, indicate the existence of "hot spot" industries. For instance, food processing industries have a significant contribution to the life cycle nutrient emissions. Although traditional manufacturing has largely been relocated overseas in the past, the overall environmental impacts are not necessarily reduced from a global perspective. In addition to technological innovations, management strategies pertaining to increasing recycling and reuse could be important in reducing the life cycle impacts associated with traditional manufacturing.

High tech has relatively insignificant direct and total environmental impacts. Further development of high tech industries in NH would greatly strengthen GDP growth while imposing minimum additional environmental burdens. The growth of high tech presents a much higher environmental payoff compared with the other three scenarios (development of traditional manufacturing, agriculture, or tourism). As most of the products of high tech industries are exported outside of the state, high tech also serves economic purposes of importing wealth from outside of the state and creating job opportunities.

Tourism provides important recreational functions for the society, but it has relatively high environmental impacts in terms of freshwater use and eutrophication potentials. This represents an interesting paradox for a state like NH. Ecosystem-based tourism is dependent upon a high water quality among other attributes and yet it is the same tourism that significantly impacts water quality.

Services, finance, and trade industries have been growing in NH in the last two decades, as they have in many other states of the U.S. These industries produce a significant amount of GDP and provide employment opportunities. They have relatively low environmental impacts per GDP produced, but the overall impacts of these industries are still significant in NH.

This indicates that although changes of industrial compositions are likely to reduce environmental burdens, it is not sufficient to decouple growth in dollars with growth in environmental throughputs. Hence, the conservation of resources and utilization of renewable resources in all types of industries are imperative given the cumulative supply chain effects throughout their life cycles. The results of this analysis suggest that strategies that may be adopted at the state level, such as the promotion of tourism or incentives to attract certain types of businesses to the state, can have significant ramifications for direct and total environmental emissions. The primary utility of this work is to provide such a perspective to state-level economic development planning that not all growth trajectories will have similar environmental implications. Many states incentivize the growth and development of business and industry, tourism, and other specific economic sectors to ensure the economic vitality of their state. While many states recognize the value of the environment to the quality of life in the state, they typically do not include the environmental impacts in their economic planning. This paper provides such a methodological framework that can be used to provide regulatory decision support and help inform more comprehensive state-level economic development plans.

A number of outstanding questions remain, however, such as whether such planning simply outsources dirtier industries (e.g., traditional manufacturing) or would result in greater tourism-related impacts occurring elsewhere. Furthermore, the IO accounts do not reflect a destiny: there are of course ways in which less impactful tourism could be fostered or that a traditional manufacturing ecosystem could minimize emissions through eco-park development strategies. However, explicitly bringing environmental burdens into a discussion about economic development planning has the potential to broaden the dialog to include, for example, GDP growth vs. genuine progress (or similar measures that include natural capital or ecosystem services in the accounting) [73] at the state level. This study serves as a first step to allow state level economic planning to move beyond simply considering GDP growth and job creation and to explicitly consider the environmental implications of economic growth in specific sectors. A more comprehensive decision-making framework that includes both socioeconomic and environmental metrics and encompasses both regional and global supply chain implications needs to be adopted in the future.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/2/542/s1: a "Calculations.xlsx" document details the economic sectors that are included in each of the eleven industrial categories based on NAICS code, the impact calculations for each of the eleven industrial categories, future projections, and the ratios between direct and total impacts.

Acknowledgments: We would like to acknowledge the National Science Foundation support via the Research Infrastructure Improvement Award #IIA-1101245. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Author Contributions: Weiwei Mo conceived and designed the study; Darline Balen, Marianna Moura, and Weiwei Mo analyzed the data; Weiwei Mo and Kevin Gardner wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ringler; C; Bhaduri, A.; Lawford, R. The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? *Curr. Opin. Environ. Sustain.* **2013**, *5*, 617–624.
2. Hoff, H. Understanding the Nexus. In *Background Paper for the Bonnx 2011 Conference: The Water, Energy and Food Security Nexus*; Stockholm Environment Institute: Stockholm, Sweden, 2011.
3. Walter V. Reid; Harold A. Mooney; et al. *Millennium Ecosystem Assessment;* Ecosystems and Human Well-Being; Island Press: Washington, DC, USA, 2005.
4. Hoekstra, A.Y.; Wiedmann, T.O. Humanity's unsustainable environmental footprint. *Science* **2014**, *344*, 1114–1117.
5. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.* **2009**, *14*, 1–33.
6. Jabareen, Y. Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities* **2013**, *31*, 220–229.
7. Agyeman, J.; Schlosberg, D.; Craven, L.; Matthews, C. Trends and directions in environmental justice: From inequity to everyday life, community, and just sustainabilities. *Annu. Rev. Environ. Resour.* **2016**, *41*, doi:10.1146/annurev-environ-110615-090052.
8. Bleischwitz, R.; Welfens, P.J.; Zhang, Z. *International Economics of Resource Efficiency: Eco-Innovation Policies for a Green Economy*; Springer Science & Business Media: Berlin, Germany, 2011.
9. Mont, O.; Bleischwitz, R. Sustainable consumption and resource management in the light of life cycle thinking. *Environ. Policy Gov.* **2007**, *17*, 59–76.
10. Brady, K.; Henson, P.; Fava, J.A. Sustainability, eco-efficiency, life-cycle management, and business strategy. *Environ. Qual. Manag.* **1999**, *8*, 33–41.
11. Leigh, N.G.; Blakely, E.J. *Planning Local Economic Development: Theory and Practice*; Sage Publications: Thousand Oaks, CA, USA, 2016.
12. Cheng, S.; Chen, D.; Li, J.; Wang, H.; Guo, X. The assessment of emission-source contributions to air quality by using a coupled MM5-ARPS-CMAQ modeling system: A case study in the Beijing metropolitan region, China. *Environ. Model. Softw.* **2007**, *22*, 1601–1616.
13. Cimorelli, A.J.; Perry, S.G.; Venkatram, A.; Weil, J.C.; Paine, R.J.; Wilson, R.B.; Lee, R.F.; Peters, W.D.; Brode, R.W. AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization. *J. Appl. Meteorol.* **2005**, *44*, 682–693.
14. Singh, K.P.; Malik, A.; Sinha, S. Water quality assessment and apportionment of pollution sources of Gomti river (India) using multivariate statistical techniques—A case study. *Anal. Chim. Acta* **2005**, *538*, 355–374.
15. Chapra, S.C. *Surface Water-Quality Modeling*; Waveland Press: Long Grove, IL, USA, 2008.
16. Du, X.; Graedel, T.E. Global in-use stocks of the rare earth elements: A first estimate. *Environ. Sci. Technol.* **2011**, *45*, 4096–4101.
17. Hashimoto, S.; Tanikawa, H.; Moriguchi, Y. Where will large amounts of materials accumulated within the economy go? A material flow analysis of construction minerals for Japan. *Waste Manag.* **2007**, *27*, 1725–1738.
18. Gibbs, D.; Deutz, P. Reflections on implementing industrial ecology through eco-industrial park development. *J. Clean. Prod.* **2007**, *15*, 1683–1695.

19. Sendra, C.; Gabarrell, X.; Vicent, T. Material flow analysis adapted to an industrial area. *J. Clean. Prod.* **2007**, *15*, 1706–1715.
20. Rosen, M.A. Assessing global resource utilization efficiency in the industrial sector. *Sci. Total Environ.* **2013**, *461*, 804–807.
21. Florax, R.J.; Travisi, C.M.; Nijkamp, P. A meta-analysis of the willingness to pay for reductions in pesticide risk exposure. *Eur. Rev. Agric. Econ.* **2005**, *32*, 441–467.
22. Krystallis, A.; Chryssohoidis, G. Consumers' willingness to pay for organic food: Factors that affect it and variation per organic product type. *Br. Food J.* **2005**, *107*, 320–343.
23. Wunder, S. *Payments for Environmental Services: Some Nuts and Bolts*; Center for International Forestry Research: Bogor, Indonesia, 2005.
24. Kahn, J.R.; Vásquez, W.F.; de Rezende, C.E. Choice modeling of system-wide or large scale environmental change in a developing country context: Lessons from the Paraíba do Sul River. *Sci. Total Environ.* **2017**, *598*, 488–496.
25. Hendrickson, C.T.; Lave, L.B.; Matthews, H.S. *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*; Resources for the Future: Washington, DC, USA, 2006.
26. Huntzinger, D.N.; Eatmon, T.D. A life-cycle assessment of Portland cement manufacturing: Comparing the traditional process with alternative technologies. *J. Clean. Prod*. **2009**, *17*, 668–675.
27. Nemecek, T.; Kägi, T.; Blaser, S. *Life Cycle Inventories of Agricultural Production Systems*; Data v2. 0; Ecoinvent Report; 2007.
28. Mattila, T.J.; Pakarinen, S.; Sokka, L. Quantifying the total environmental impacts of an industrial symbiosis-a comparison of process-, hybrid and input− output life cycle assessment. *Environ. Sci. Technol.* **2010**, *44*, 4309–4314.
29. Mo, W.; Wang, H.; Jacobs, J.M. Understanding the influence of climate change on the embodied energy of water supply. *Water Res.* **2016**, *95*, 220–229.
30. Guinée, J.B. Handbook on life cycle assessment operational guide to the ISO standards. *Int. J. Cycle Assess.* **2002**, *7*, 311–313.
31. Baumann, H.; Tillman, A.-M. *The Hitch Hiker's Guide to LCA. An orientation in Life Cycle Assessment Methodology and Application*, 1rst ed.; Studentlitteratur Ab: Lund, Sweden, 2004.
32. Yue, D.; Pandya, S.; You, F. Integrating hybrid life cycle assessment with multiobjective optimization: A modeling framework. *Environ. Sci. Technol.* **2016**, *50*, 1501–1509.
33. Seppäläa, J.; Melanen, M.; Mäenpää, I.; Koskela, S.; Tenhunen, J.; Hiltunen, M.R. How can the eco-efficiency of a region be measured and monitored? *J. Ind. Ecol.* **2005**, *9*, 117–130.
34. Blackhurst, B.M.; Hendrickson, C.; Vidal, J.S.I. Direct and indirect water withdrawals for US industrial sectors. *Environ. Sci. Technol.* **2010**, *44*, 2126–2130.
35. Chen, S.; Chen, B. Coupling of carbon and energy flows in cities: A meta-analysis and nexus modelling. *Appl. Energy* **2017**, *194*, 774–783.
36. Smetana, S.; Tamásy, C.; Mathys, A.; Heinz, V. Sustainability and regions: Sustainability assessment in regional perspective. *Reg. Sci. Policy Pract.* **2015**, *7*, 163–186.
37. Agostinho, F.; Ortega, E. Integrated food, energy and environmental services production as an alternative for small rural properties in Brazil. *Energy* **2012**, *37*, 103–114.
38. Kurka, T. Application of the analytic hierarchy process to evaluate the regional sustainability of bioenergy developments. *Energy* **2013**, *62*, 393–402.
39. Suh, S. Developing a sectoral environmental database for input–output analysis: The comprehensive environmental data archive of the US. *Econ. Syst. Res.* **2005**, *17*, 449–469.
40. Lave, L.B. Using input-output analysis to estimate economy-wide discharges. *Environ. Sci. Technol*. **1995**, *29*, 420A–426A.
41. Suh, S. *Comprehensive Environmental Data Archive (CEDA) 3.0.*; User's Guide; Institute of Environmental Science (CML), Leiden University, Leiden: The Netherlands, 2004.
42. Hubacek, K.; Giljum, S. Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecol. Econ.* **2003**, *44*, 137–151.
43. Hoekstra, R.; van den Bergh, J.C. Constructing physical input-output tables for environmental modeling and accounting: Framework and illustrations. *Ecol. Econ.* **2006**, *59*, 375–393.
44. BEA. *Bureau of Economic Analysis, Regional Economic Accounts* 2015. Available online: http://www.bea.gov/regional/index.htm (accessed on 1 December 2017).

45. DeSimone, L.D.; Popoff, F. *Eco-Efficiency: The Business Link to Sustainable Development*; MIT Press: Cambridge, MA, USA, 2000.
46. Schmidheiny, S. *Changing Course: A Global Business Perspective on Development and the Environment*; MIT Press: Cambridge, MA, USA, 1992.
47. Zhang, B.; Bi, J.; Fan, Z.; Yuan, Z.; Ge, J. Eco-efficiency analysis of industrial system in China: A data envelopment analysis approach. *Ecol. Econ.* **2008**, *68*, 306–316.
48. Gössling, S.; Peeters, P.; Ceron, J.P.; Dubois, G.; Patterson, T.; Richardson, R.B. The eco-efficiency of tourism. *Ecol. Econ.* **2005**, *54*, 417–434.
49. Ayres, R.; Ferrer, G.; van Leynseele, T. Eco-efficiency, asset recovery and remanufacturing. *Eur. Manag. J.* **1997**, *15*, 557–574.
50. Kerr, W.; Ryan, C. Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. *J. Clean. Prod.* **2001**, *9*, 75–81.
51. Maxime, D.; Marcotte, M.; Arcand, Y. Development of eco-efficiency indicators for the Canadian food and beverage industry. *J. Clean. Prod.* **2006**, *14*, 636–648.
52. Polasky, S.; Binder, S. Valuing the environment for decisionmaking. *Issues Sci. Technol.* **2012**, *28*, 53–62.
53. US Census Bureau. *State & County QuickFacts*;. Available online: https://www.census.gov/data.html (accessed on 1 December 2017).
54. US Bereau of Economic Analysis. *Regional GDP and Personal Income Data*; US Bereau of Economic Analysis: 2014; Washington, DC, USA. Available online: http://www.bea.gov/regional/index.htm (accessed on 1 December 2017).
55. Foster, D.R. Land-use history (1730–1990) and vegetation dynamics in central New England, USA. *J. Ecol.* **1992**, *80*, 753–771.
56. Donahue, B.; Burke, J.; Anderson, M.; Beal, A.; Kelly, T.; Lapping, M.; Ramer, H.; Libby, R.; Berlin, L. *A New England Food Vision*; University of New Hampshire: Durham, NH, USA, 2014,
57. Mahoney, J.C.; Gerding, M.J.; Jones, S.H.; Whistler, C.A. Comparison of the pathogenic potentials of environmental and clinical Vibrio parahaemolyticus strains indicates a role for temperature regulation in virulence. *Appl. Environ. Microbiol.* **2010**, *76*, 7459–7465.
58. Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. . Climate Change 2013: The Physical Science Basis. In *Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5)*; Cambridge University Press: New York, NY, USA, 2013.
59. NH Department of Environmental Services (NHDES). *New Hampshire Department of Environmental Services, Global Climate Change and Its Impact on New Hampshire*; NHDES: Concord, NH, USA, 2008. Available online: http://des.nh.gov/organization/commissioner/pip/factsheets/ard/documents/ard-23.pdf (accessed on 1 December 2017).
60. NH Department of Environmental Services (NHDES). *New Hampshire Department of Environmental Services, The New Hampshire Climate Action Plan*; NHDES: Concord, NH, USA, 2009. Available online: http://des.nh.gov/organization/divisions/air/tsb/tps/climate/action_plan/nh_climate_action_plan.htm (accessed on 1 December 2017).
61. NH Department of Environmental Services (NHDES). *New Hampshire Department of Environmental Services, Regional Greenhouse Gas Initiative (RGGI)*; NHDES: Concord, NH, USA, 2008. Available online: http://des.nh.gov/organization/divisions/air/tsb/tps/climate/rggi/ (accessed on 2 December 2017).
62. Bureau of Labor Statistics. *Consumer Price Index*; Bureau of Labor Statistics: Washington, DC, USA, 2015. Available online: http://www.bls.gov/cpi (accessed on 1 December 2017).
63. Eckelman, M.J.; Sherman, J. Environmental impacts of the US health care system and effects on public health. *PLoS One* **2016**, *11*, e0157014.
64. Wang, R.; Zimmerman, J.B. Economic and environmental assessment of office building rainwater harvesting systems in various US cities. *Environ. Sci. Technol.* **2015**, *49*, 1768–1778.
65. CMU; CMUGDI. Economic Input-Output Life Cycle Assessment (EIO-LCA) 2017. Available online: http://www.eiolca.net (accessed on 1 December 2017).
66. Guo, J.; Planting, M.A. *Using Input-Output Analysis to Measure US Economic Structural Change over a 24 Year Period*; paper presented at the 13th International Conference on Input-Ouptut Techniques, Macerata, Italy, August 21–25, 2000.

67. Huijbregts, M.A.; Hellweg, S.; Frischknecht, R.; Hendriks, H.W.; Hungerbuhler, K.; Hendriks, A.J. Cumulative energy demand as predictor for the environmental burden of commodity production. *Environ. Sci. Technol.* **2010**, *44*, 2189–2196.
68. Peter, C.; Fiore, A.; Hagemann, U.; Nendel, C.; Xiloyannis, C. Improving the accounting of field emissions in the carbon footprint of agricultural products: A comparison of default IPCC methods with readily available medium-effort modeling approaches. *Int. J. Life Cycle Assess.* **2016**, *21*, 791–805.
69. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.V.Z.R.; Van Zelm, R. *ReCiPe 2008, A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*; Mees Ruimte & Milieu: Zoetermeer, Netherlands, 2009.
70. Lippiatt, B.C. *BEES 2.0 Building for Environmental and Economic Sustainability: Technical Manual and User Guide*; NIST: Gaithersburg, MD, USA, 2000.
71. New Hampshire Employment Security (NHES). *State of New Hampshire, New Hampshire Employment Projections by Industry and Occupation*; NHES: Concord, NH, USA, 2014. Available online: http://www.nhes.nh.gov/elmi/products/proj.htm (accessed on 1 December 2017).
72. WISERTrade: State HS Database. 2015; Available online: http://www.wisertrade.org/home/portal/index.jsp (accessed on 1 December 2017).
73. Cobb, C.; Halstead, T.; Rowe, J. *The Genuine Progress Indicator*; Redefining Progress: San Francisco, CA, USA, 1995.