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USING ECOSYSTEM LANDSCAPE MODELS TO INVESTIGATE INDUSTRIAL ENVIRONMENTAL IMPACTS

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ABSTRACT

This article explores the use of ecosystem landscape models to estimate the environmental impacts of industrial activities at the regional / local scale. Integrated ecosystem and industrial modeling is first introduced within the context of life cycle assessment. Then, the use of integrated modeling to overcome problems stemming from the lumped parameter, static, site non-specific nature of life cycle assessment is discussed. Finally, the results of linking a handful of industrially relevant material and information flows demonstrate the ability of current ecosystem landscape models to respond to industrial burdens and estimate some environmental impacts.

1. Introduction

The design of a product impacts the environment during manufacture. Energy and raw materials needed to realize the product come from the environment, and the environment serves as a sink for wastes. *As a result of governmental pressures or a desire for environmental stewardship, many companies are attempting to reduce the environmental impact of their products. However, a fundamental problem that is facing designers and engineers alike is how to assess the environmental impact of their products in the first place. One approach is life-cycle assessment (LCA).* LCA has become an important environmental assessment tool for industry, environmental policy and even international environmental policy [1, 2]. Unfortunately, conventional LCA (as encoded in the ISO 14040-14043 standards) suffers from a number of documented limitations and failings [3, 4, 5]. Drawing from a previous summary [6], one finds that a conventional LCA:

- Reduces or ignores spatial discrimination
- Is steady state – not dynamic
- Ignores background levels of pollution
- Ignores fate
- Focuses on only environmental considerations (not economic or societal)
- Regards all processes as linear (such as dose-response curves)
- Is laden with value judgments and subjectivity
- Is costly in terms of money and time
- Requires difficult or impossible to find data

Not all environmental impact assessments are or need to be focused on a total life-cycle perspective. For example, suppose that a manufacturer wants to know and reduce the impact of its operations on the local environment to provide a healthier community and quality of life. The general question for this scenario is: how would one evaluate the environmental impact of manufacturing a given product design in a specific region or locale? Ideally, one may want a model to explore the effects of changes in production volume, product design, process parameters, management practices and even technology.

Without considering space, time and place, a conventional LCA would probably not guide design changes in such a way as to reduce the environmental burdens to which the selected

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location is most sensitive. To overcome this lack of considering space, time and place, integrated ecosystem and industrial modeling (eco-industrial modeling) was proposed as an environmental impact assessment tool that includes spatial, temporal and place specific considerations [6].

In this article, the concept and background of eco-industrial modeling is briefly reintroduced, followed by a case study in which an existing ecosystem model is linked with manufacturing related industrial flows to simulate the impacts of a manufacturing resource extraction and a waste release. The article closes with a discussion of the results and a critical review of eco-industrial modeling's ability to answer the question, 'how would one evaluate the environmental impact of manufacturing a given product design in a specific region or locale?'

2. The Importance of Space, Time and Place

The focus of this article is on environmental impact assessment problems that stem from a lack of spatial, temporal and site specific considerations. Failures to consider spatial and temporal dimensions are noted in the literature [7, 4, 5]. By ignoring spatial dimensions, traditional LCIA fails in two ways:

- It fails to consider the influence of landscape patterns upon environmental impacts. As discussed by Turner and coauthors, landscape patterns influence the function of ecosystems [8].
- Furthermore, the method fails to account for the location of resource extractions and/or emissions in the landscape. A spatially explicit eco-industrial model could account for industrial patterns and locations.

Ignorance of temporal considerations limits the usefulness of LCA as a planning tool. By ignoring time, one loses the ability to engage in predictive modeling [9]. Without dynamic considerations, one cannot consider changes in ecosystem functions in response to long-term stresses. And, one cannot estimate the effects of accumulating pollutants and existing background pollution.

Disregarding place also limits the usefulness of LCA. "LCA does not provide the framework for … identifying which impacts can be expected due to the functioning of a facility in a specific locality" [5]. Without information about a specific locale, LCA cannot account for the unique sensitivities of a particular area [7]. For example, water use in a dessert ecosystem would have markedly different consequences than the same intensity and manner of use in a temperate forest ecosystem. An eco-industrial model with the appropriate regional / local data, however, could provide an estimate of a locality's response.

Efforts to correct these failings are underway. A more detailed discussion of the problems caused by and attempts at incorporating space, time and place in LCA can be found elsewhere [6]. As noted before, the approach taken to address these problems in this article is to use a dynamic eco-industrial model. The following questions arise when taking this approach:

1. What are ecosystem models?
2. How can they be linked to industrial models (and/or vice versa)?
3. Will the integrated model provide the ability to perform environmental impact assessments?

In this paper, a first attempt at answering these questions is presented. The main focus will be on using ecosystem landscape models to address the third question. Specifically, the Patuxent Landscape Model (PLM) developed by Voinov and coworkers is used [10].

3. Ecosystem Models

It is important to define what is meant by the phrase "ecosystem model" versus, for example, environmental model. Ecosystem models represent, to some degree, the complex of a community of organisms and the physical environment functioning as a unit. The systems focus present in ecosystem models distinguishes them from biogeochemical, water quality and other environmental models which focus upon the cycling of one material or changes in one medium. Based upon Jorgenson's classification of environmental models, one divides ecosystem models into three categories (See Table 1)[11].

Table 1: Types of Ecosystem Models

Type	Description	Examples
Terrestrial Ecosystems	Terrestrial ecosystem models include representations of agricultural and natural ecosystems. They specialize in estimating the dynamics of these ecosystems.	• GEM – General ecosystem model [12]
Landscape Models	Landscape models specialize in simulating changes in a region; spatial patterns and distributions are implicitly or explicitly included.	• FINICH – a Californian Chaparral Region model [13]
Ecosystem Landscape Models	Ecosystem landscape models represent a fusion of terrestrial ecosystem models and landscape models. Representations of smaller scale dynamics combine with spatial representations used to simulate the influence of patterns and larger scale dynamics.	• Malaysian Peninsula Forestry Model [14] • Patuxent Landscape Model [10]

4. Linking Ecosystem and Industrial Models

Clearly, one can conceive a variety of different ways to link industrial models to ecosystem models. All are dependent on what type of industrial model is to be linked with what type of ecosystem model. Generally, an eco-industrial model is defined by a) the level of detail and b) the existing structure of the two individual models selected for integration.

At the fundamental level, mass flows to and from a facility and information denoting the location of the facility provide the most basic links needed for joining an industrial model with an ecosystem landscape model (See Figure 1).

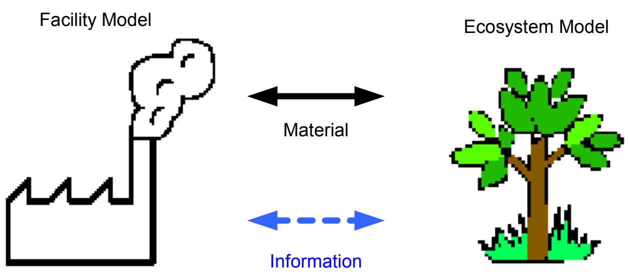

Figure 1: Abstract Linked Model

Flows to the facility represent resources such as water and biomass extracted from the surrounding environment while flows from the facility represent emissions to the environment.

The ability to simulate the impact of industrial facilities hinges upon the ability to represent industrially relevant resource and waste flows to an existing ecosystem model and to detect ecosystem model responses to these new inputs. Establishing these links and determining the ecosystem model's ability to detect these changes serve as the first step in the creation of eco-industrial models and as the focus of the remainder of this article, which investigates the augmentation of an existing ecosystem landscape model with links to industrial models to determine their environmental impact.

5. Case Study: Integrated Eco-Industrial Landscape Model Using the Patuxent River Watershed

5.1 The Patuxent Ecosystem Landscape Model

Figure 2 illustrates the structure of the ecosystem landscape model used during the course of this work, which is the Patuxent Landscape Model (PLM). Voinov and coauthors created the Patuxent Landscape Model (PLM) "…to simulate fundamental ecological processes on the watershed scale" [10]. They "partitioned" a landscape "…into a grid of square unit cells…" to achieve a spatially explicit ecosystem representation [10]. An ecosystem unit model represents the dynamics of the ecosystem (ie. forest, grassland, etc.) in each grid square [12]. With the most recent version of the ecosystem landscape model, one builds the unit models by assembling ecosystem process modules [15]. The process modules contain parameters based upon data specific to the modeled landscape.

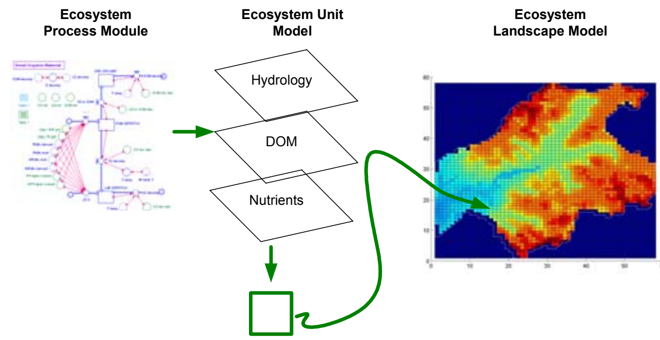

Figure 2: Ecosystem Landscape Model Implemented Using the SME

Reading Figure 2 from left to right, one builds an ecosystem landscape model by selecting and obtaining parameters for a set of ecosystem process modules; these modules are implemented using commercially available STELLA modeling software. The Spatial Modeling Environment (SME) developed by Maxwell and Costanza fuses the process modules into a unit model [16]. The SME then assembles the unit models into a landscape grid. The SME is a software construct that "supports 1) modular, hierarchical model construction and archiving/linking of simulation modules, 2) graphical, icon-based model construction, 3) transparent distributed computing, and 4) integrating multiple space-time representations" [17]. If one could link this type of model to a representation of an industrial facility, one would gain a spatially explicit, dynamic and place specific tool capable of representing the environmental impacts of industrial decisions.

5.2 Linking Industrial Inputs and Outputs in the PLM

One first identifies the industrially relevant material flows that existing ecosystem process modules can accommodate. The PLM, a component of which is used in this study, possesses process modules for water, nitrogen, phosphates and biomass [10, 19]. All of these materials are of industrial or agricultural importance.

After identifying compatible flows, one modifies the appropriate process modules using High Performance Systems' STELLA modeling software. The first step is the creation of a flow variable, and the second is the creation of placeholder that will be used later in the integration process to locate the flow in the landscape. Other steps include the modification of flow variable logic and the addition of constants and parameters needed to support the new variable.

Having modified the process modules, one builds an ecosystem landscape model using the Spatial Modeling Environment by following the procedures described by Maxwell [18]. Activation of the anthropogenic material flows in the modified process modules requires modification of the configuration files generated by the SME. Additionally, one includes portable pixmaps (PPM) in the data files created by the SME for the modified landscape model in order to fix the location of resource extractions and waste releases. Another approach to solving the location problem involves modifying the landscape type maps.

6. Assessing Environmental Effects of Industrial Operations: Experiments and Results

Linking industrial flows to an ecosystem landscape model is only part of the first step toward integrated ecosystem and industrial modeling. Having created links, one must evaluate the response, if any, of the simulated ecosystem to the simulated burdens. In this section, the response of an ecosystem landscape model to two types of industrial burdens is investigated with the aim of discerning whether the ecosystem model registers a change.

6.1 Linking Industrial Inputs and Outputs in the PLM

Groundwater extraction is the first of the two burdens. A subwatershed unit of the Patuxent Landscape Model developed by Voinov and coworkers, called the Hunting Creek landscape model, served as the experimental apparatus for this investigation [10]. The Hunting Creek model was modified to incorporate anthropogenic groundwater removals in individual cells of the discretized landscape.

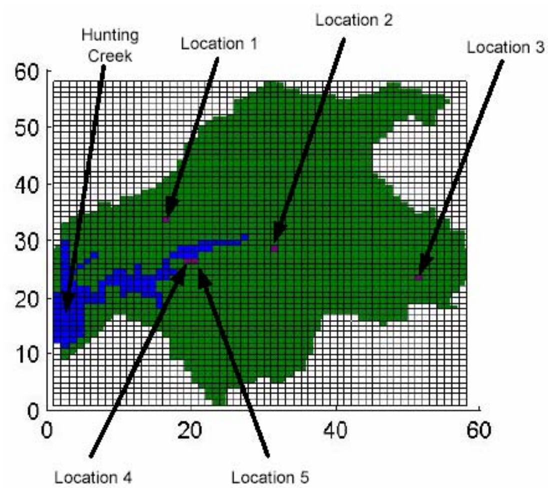

Figure 3: Extraction Locations in Hunting Creek Watershed

Three different extraction intensities (High = 37,800 m^3/day, Med. = 155 m^3/day, Low = 16.5 m^3/day) were investigated; the intensities roughly correspond to the water consumption of a pulp and paper mill, power plant with cooling towers and a carpet manufacturer, respectively. Each of the three intensities was applied at locations 1-4 for 365 days or until the water table in a cell dropped to nearly zero (See Figure 3). Ecosystem response for the landscape was measured in terms of changes in saturated water level (SAT_WATER), Hunting Creek surface water level (SURFACE_WATER), surface nitrogen (DIN_SF) and net primary production (NPP) (See Table 2 and Figure 4).

The values in Table 2 are differences between the disturbed Hunting Creek watershed and the undisturbed Hunting Creek watershed. One reads the table by selecting a response variable and a corresponding intensity at a particular location. For example, the groundwater level change caused by a medium intensity extraction at Location 1 is -1.2 m.

Table 2: Sum of the Changes for All Cells in the Area Affected by Ground Water Extraction

Response Variable	Int.	Location 1	Location 2	Location 3	Location 5
SAT_WATER [m]	Low	-0.1	-0.3	-0.4	-0.4
	Med.	-1.2	-2.9	-4.0	-3.6
	High	-35.7	-21.7	-29.9	-14.7
SURFACE_WATER [m]	Low	-0.4	0.0	0.0	0.0
	Med.	-1.3	-0.2	-0.1	-0.2
	High	-3.3	-1.9	-0.2	-1.1
DIN_SF [g/m^2]	Low	-1.4	-0.1	0.0	0.0
	Med.	-4.6	-0.2	-0.2	-0.5
	High	-11.2	-3.3	-0.3	-1.9
TOT_NPP [kg/m^2]	Low	1.1	0.0	0.0	0.0
	Med.	1.8	0.0	0.0	0.0
	High	3.9	-0.2	0.0	0.0

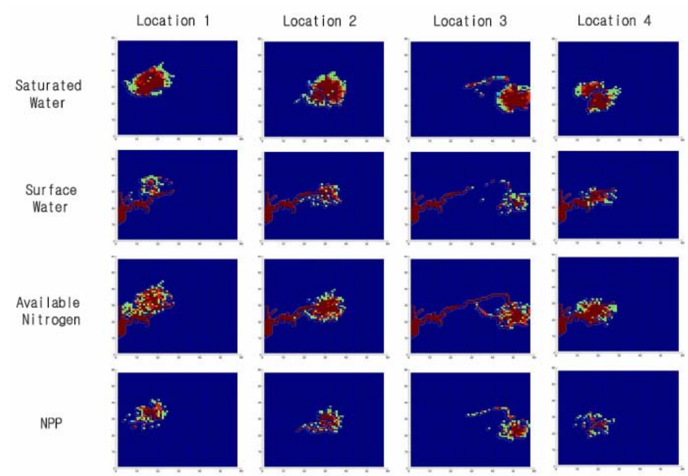

Figure 4: Extent and Pattern of Changes Caused by Groundwater Extractions at Different Locations (Brown = all intensities, Pink = Med. and High, Green = High)

6.2 Industrially Induced Biomass Mortality

An increase in biomass mortality fraction serves as a proxy for damage to an ecosystem caused by the release of toxic materials. Though a crude approximation, the manipulation of factors such as mortality in a model originally meant to represent contaminant free systems is not without precedent. DeAngelis manipulates such factors to estimate the impact of contaminants on bass populations [20]. The Hunting Creek model again serves as the experimental apparatus. Three different biomass mortality fractions were selected by scaling the natural biomass mortality. Low mortality ($5.3x10^{-8}$) is one-tenth natural mortality while medium mortality ($5.3x10^{-6}$) is 10 times natural. High mortality ($5.3x10^{-5}$) is one hundred times natural mortality. Non-photosynthetic biomass (NPH_BIOMAS), deposited organic material (DEP_ORG_MAT), surface nitrogen (DIN_SF) and net primary production (NPP) measure the response of the ecosystem (See Table 3).

Table 3: Sum of the Changes for All Cells in the Area Affected by Industrially Induced Mortality (Note: Values Maintained at Unrealistic Precision for Rhetorical Reasons)

Response Variable	Int.	Location 1	Location 2	Location 3	Location 5
NPH_BIOMAS [kg/m^2]	Low	0	0	0	0
	Med.	-0.0014	-0.0011	-0.001	-0.0013
	High	-0.0177	-0.0121	-0.0122	-0.0146
DEP_ORG_MAT [kg/m^2]	Low	0.000001	0.000001	0.000001	0.000001
	Med.	0.000093	0.000093	0.000093	0.000092
	High	0.000928	0.000928	0.000929	0.000929
DIN_SF [g/m^2]	Low	0	0.000001	0	0
	Med.	0.002	0.00007	0.0002	0.0002
	High	0.021	0.000738	0.0014	0.0023
TOT_NPP [kg/m^2]	Low	0	0	0	0
	Med.	0.0002	0.0007	0.0007	0.0005
	High	0.002	0.0075	0.0073	0.0048

7. Discussion of Groundwater and Mortality Experiments

The results in Section 5 reveal that the ecosystem landscape model responds to burdens of common industrial intensity. Ground and surface water levels fall for all three intensities, as one would expect, and surface nitrogen and net primary production (NPP), the total amount of biomass added to cell in a time period, also change (See Table 2). The somewhat surprising NPP increase at location 1 might be a result of reductions in the water-logging of roots caused by the declining water tables. Figure 4 illustrates that differences in location affect the extent and pattern of environmental changes, and the data in Table 2 shows that differences in location also affect the magnitude of changes. Together, they lend support to arguments for including space and place considerations in LCA. Viewing Table 3, one learns that the model responds to changes in mortality fraction in both expected and unexpected ways. As one would expect, declines in non-photosynthetic biomass became more pronounced as the mortality fraction increased. Unexpectedly, NPP actually increased with increasing mortality fraction. The increase in NPP is a consequence of the form of the function used to model net primary productiv*ity* – the rate at which biomass is added. As total biomass declines, net primary productivity initially increases. Consequently, increases in mortality can lead to increases in NPP, the total biomass produced in a specified period.

However, the changes reported for the model subject to increased mortality fraction are quite small. In fact, given the uncertainties in the model and variability in the data input to the model, the changes listed in Table 3 are insignificant. Furthermore, a model that predicts increases in NPP despite the presence of toxins should rouse suspicions. The rise in NPP likely speaks to the crude method of representing toxins. A superior approach would both raise mortality and reduce growth. Additionally, it is not clear whether the sub-surface hydrology process module is still valid when a cell loses nearly all of the water in its saturated zone.

8. Potential Future Applications

Ideally, the structure of an integrated eco-industrial model would possess sufficient detail and flexibility to assess the environmental impact on the ecosystem arising from changes in production volume, product design, process parameters, management practices and even technology. One would also exercise the model to explore means of reducing environmental impacts influenced by these factors. However, as shown in this paper, this goal has not yet been achieved.

In the future, one foresees using improved industrial elements in eco-industrial models to positively affect process design and management. Consider the case of a metal finisher planning to install water recycling technology. An eco-industrial model including a valid industrial process sub model would indicate the magnitude and extent of the environmental impact avoided by using less water. Improved modules for waste materials would reveal impact reductions caused by declining waste water releases. Similar predictions for changes in management practices are also possible.

Results presented in Section 6 clearly show the importance of location. This correlation between location and environmental effects holds significance for product design. Some sites possess unique sensitivities to industrial activities. Water use in deserts or arid regions may deprive communities and degrade ecosystems. Waste releases in diverse habitats such as rainforests may be comparatively more damaging than elsewhere. Passing information about the unique sensitivities of a locale or region to the designer in a concise fashion would give designers and engineers the ability to tailor a product not only to suite a market but also the region of manufacture. Functionally equivalent though environmentally different materials and processes could be explored by the designer. An eco-industrial model provides the information that could eventually be filtered and passed to the designer. Such simulations allow designers to explore multiple design concepts or at least embodiments.

9. Closure

In essence, promise and problems issue from what has been shown in this paper. One comes to see the promise of using spatially explicit, dynamic site specific models to estimate impacts, and one learns that existing models possess the ability to partially represent impacts. This is especially clear in the groundwater experiment where one sees the influence of locations on impacts as well as the spatial character of the impacts. However, one also confronts the problems caused by data inaccuracies and crude representations for toxic inputs to the ecosystem. The presence of both problems and promise together provide a stronger rationale for continuing research in eco-industrial modeling than either could alone.

Looking forward, future efforts should center on taking advantage of the promise and ameliorating the problems. Since the modified landscape models can estimate some impacts, exploration of the manufacturing and design decisions that one can support using the current model is in order. One can explore these opportunities by first increasing the detail level of the manufacturing facility model. Then, one can exercise the resulting more detailed eco-industrial model to determine the scale of the decision needed to illicit a noticeable and significant change in the ecosystem component of the model. Previously noted problems stem from data inaccuracies and a crude representation of toxic materials. Future work should also include efforts to improve data quality and develop process modules that account for the influence of toxins in the environment.

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