Industrial Ecosystems and Food Webs

An Expansion and Update of Existing Data for Eco-Industrial Parks and Understanding the Ecological Food Webs They Wish to Mimic

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Summary

Cyclical industrial networks are becoming highly desirable for their efficient use of resources and capital. Progress toward this ideal can be enhanced by mimicking the structure of naturally sustainable ecological food webs (FWs). The structures of cyclic industrial networks, sometimes known as eco-industrial parks (EIPs), are compared to FWs using a variety of important structural ecological parameters. This comparison uses a comprehensive data set of 144 FWs that provides a more ecologically correct understanding of how FWs are organized than previous efforts. In conjunction, an expanded data set of 48 EIPs gives new insights into similarities and differences between the two network types. The new information shows that, at best, current EIPs are most similar to those FWs that lack the components that create a biologically desirable cyclical structure. We propose that FWs collected from 1993 onward should be used in comparisons with EIPs, given that these networks are much more likely to include important network functions that directly affect the structure. We also propose that the metrics used in an ecological analysis of EIPs be calculated from an FW matrix, as opposed to a community matrix, which, to this point, has been widely used. These new insights into the design of ecologically inspired industrial networks clarify the path toward superior material and energy cycling for environmental and financial success.

Introduction

Ecological food webs (FWs) and collections of interacting industries both represent collections of entities (species and industries, respectively) that exchange materials and energy (Frosch and Gallopoulos 1989). Industrial ecology hypothesizes that networks of industries designed to be analogous to the structure and properties of FWs may approach a similarly sustainable and efficient state (Frosch 1992). Industries that share and/or exchange inputs and outputs (e.g., raw materials, products, process wastes, or water) are classified together as an industrial ecosystem. When these interacting industries are colocated, then the industrial ecosystem is also referred to as an eco-industrial park (EIP)[1] (Chertow 2000). A commonly cited example of an EIP is Kalundborg, Denmark. Concerns over limited groundwater supplies in 1961 initiated water reuse measures between the major companies in Kalundborg, creating mutually beneficial relationships (Mitchell 2003; Hardy 2001; Jacobsen 2006). Since 1961, these relationships have continued to form, and over 30 material and energy exchanges are now documented. The relationships have created an ecosystem-like structure and have resulted in a reduction in yearly carbon

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dioxide emission by 240 kilotonnes and a savings of 264 million gallons of water through recycling and reuse (Drake 1990; Jacobsen 2006; Bastolla et al. 2009).

Thus far, ecology has acted as more a metaphor than a source for sound EIP design principles (Jensen et al. 2011; Hess 2010; Isenmann 2003). Identifying similarities and differences in the organization of EIPs and FWs would advance the design of sustainable industry relationships. Comparing the structure of EIPs and FWs using a variety of ecological parameters may guide the development of EIPs (Reap 2009). Analyses of this type thus far have been limited (e.g., Hardy and Graedel 2002), and a rigorous and comprehensive analysis has not yet been performed.

Implementation of any FW properties requires the use of real-world EIPs for testing. A set of real EIPs also allows for a much needed investigation of how the functions of EIPs are dictated by their structure (e.g., the topology or input-output [I-O] connections) and how applied ecological principles can change their structure and therefore affect their function, for example, in terms of efficiencies. A robust collection of EIPs is needed for a comprehensive study, particularly given that current literature focuses heavily on the Kalundborg EIP (McManus and Gibbs 2008). The small data collections of EIPs that do exist commonly have a high percentage of hypothetical systems. This article examines the structure of material and energy flows in 48 EIPs (listed in supporting information S1 [tables S1-1 and S1-2] and S2 on the Journal's website); more than twice the size and far more detailed than those analyzed previously (Hardy and Graedel 2002; Rotkin et al. 2004; Lowe 2001; Korhonen and Snäkin 2005; Chertow 2000; Reap 2009). This EIP data set contains complete structural information, such that FW metrics could be applied and results compared to ecological food webs. Previous EIP-FW studies used small numbers of FWs (Reap 2009; Hardy and Graedel 2002; Fath and Halnes 2007). The data set of 144 ecosystem FWs offered here (listed in supporting information S3 on the Web) has been expanded and updated, providing new insight into the structural similarities and differences between EIPs and ecological FWs.

Background: Ecological Analysis of Eco-Industrial Parks

Ecological literature defines metrics that examine ecosystem properties and species interactions (see, e.g., Odum 1969; Pimm 1982; Warren 1990; Schoener 1989; Briand and Cohen 1987; Cohen et al. 1993; Ulanowicz 1997). Interspecies interactions within these highly complex networks are graphically organized into FW diagrams. FWs capture biodiversity, species interactions (particularly feeding relationships), and the structure of links (e.g., between predators and prey). Metrics developed by ecologists describe and analyze the structures governing FWs, properties of which are highly desirable in industrial systems and may be transferred by mimicking the FW structure. The benefits of an FW-like structure for EIPs have been extensively documented (e.g., Van Beers et al. 2007; Yang and Feng 2008; Jacobsen 2006; Ehrenfeld and Gertler 1997; Chertow 2000; ZERI 2012; Park et al. 2008; Chertow and Lombardi 2005; Zhu et al. 2007), showing that the exchanges characteristic to this structure contribute to an overall reduction of environmental burdens owing to energy and material consumption. For example, a carpet recycling network designed to mimic FWs was found to positively correlate ($R^2 = 0.96$) with standard cost- and emissions-minimizing designs using a unique structural configuration, which could provide inherent network robustness and stability (not considered by conventional industry optimization models) (Reap 2009). Ecosystem robustness and stability could lend themselves to easing the damage caused by supply-chain disruptions, which reduce the share price of the affected companies so significantly that 80% of companies worldwide consider better protection of supply chains top priority (Bhatia et al. 2013). The literature indicates that these benefits can occur on an absolute basis as well as a relative basis (per unit of production). Therefore, one can argue that formation of these systems generally leads to environmental improvements.

Quantitative ecological analyses of EIPs focus on the translation and comparison of structural FW metrics. Hardy and Graedel analyzed 18 hypothetical and realized EIPs using the metric connectance (Hardy and Graedel 2002). Connectance is a measure of the active interactions in a community, as compared to all possible interactions (see equations (10) and (11). Comparing the EIPs to a set of FWs collected by Briand (Briand 1983), Hardy and Graedel showed that industrial systems with symbiotic or "ecosystem-like" relationships displayed similar mean values for connectance. Although this analysis was significant in pioneering the use of FW metrics to analyze EIPs, it illustrates some difficulties in applying ecological methods to human industrial systems.

FW ecologists have not always been clear about the assumptions and motivations of their analyses, particularly before the early 1990s (Cohen et al. 1993; Polis 1991). As such, difficulties in application to industrial networks commonly occur (Hardy and Graedel 2002; Wright et al. 2009; Van Berkel 2009; Graedel 1996; Dai 2010). The first major difficulty is in identifying the appropriate calculations for FW metrics for the structure of EIPs, which are similar, but not identical, to that of FWs. For example, parameters describing linkage patterns in FWs are calculated differently depending on the types of interactions that are represented in the graphical/structural depiction (web) of the community. Hardy and Graedel (2002) use an equation that is not appropriate for understanding the I-O structure of FWs (see the *Ecological Network Analysis* section below), making it difficult to benchmark EIPs relative to their FW analogs. This issue can be seen frequently in the literature (Hardy and Graedel 2002; Wright et al. 2009; Van Berkel 2009; Graedel 1996; Dai 2010), suggesting a need to more carefully define appropriate parameters and conditions under which various types of analyses may be used. The second major issue is making comparisons with FW data sets that may not accurately represent real biological communities. The rapid rise in the extent and importance of FW analyses in the early 1990s sparked a major effort among ecologists to assess the quality of existing data and suggest appropriate and standardized data collection methods (Polis 1991; Cohen et al. 1993). These works document major inconsistences in data collection methods and potentially significant biases in the analytical results of ecosystems a priori. Greater emphasis has been placed upon the quality of FW data since these two important articles. This shift has been captured by the FW data set used here.

Methods

EIPs and industrial ecosystems can be represented by FW diagrams; the predator-prey exchanges between species become the exchanges of materials and energy between companies. With this analogy, metrics used by ecologists may be applied to analyze and influence structure, and thus behavior, of industrial networks. For example, the complexity of an ecosystem is measured through the density of its linkages, the quantity and types of species (diversity), and the systems connectance (Dunne et al. 2002a). Prey-to-predator ratios can be used in EIP design as well, an overabundance of companies acting as predators (companies that receive materials and/or energy) and not enough companies acting as prey (companies that provide materials and/or energy) suggests that too few prey firms are providing feedstock to too many predator firms creating the potential for instability. FW properties relating to detritus are of interest if one makes an analogy between the function of a detritus or decomposer species in an FW and a recycler in an EIP; a carpet recycler in a carpet distribution network is an example of such. Cannibalism in an EIP would be analogous to a company reusing its own waste or secondary products for purposes other than their primary use. An example of such would be the reuse of wastewater for cooling within the same plant. The use of statistical summaries of these properties and other metrics as a guide for the development of EIPs has been suggested as a way to form both cost-effective and sustainable industrial networks (Reap 2009).

Ecological Network Analyses

The flows of materials and energy in an ecosystem and summarized by an FW can be represented in an FW matrix **[F]**. The interactions are organized between predators (columns, resources flow to predators) and prey (rows, resources flow from prey). Figure 1 shows a hypothetical FW represented as a directional digraph (left) and converted into an FW matrix (right). Because a species (N) can be both predator and prey, the result is a square matrix. A value of 1 indicates the existence of a directional flow from row to column and a zero indicates no connection. In other words, if predator-j feeds on prey-i, then $f_{ij} = 1$; the interaction (or link, L) is accounted for exactly once in the FW matrix. The maximum number of links, L, scales as $(N)*(N\text{-}1)$ if cannibalism is not allowed and N^2 if it is (noted as a 1 on the diagonal).

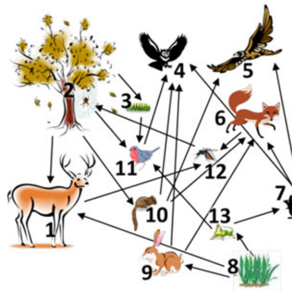
Ecologists also can express material and energy flows using a community matrix **[C]**. A community matrix contains *all connections* in an FW, documenting each observed interaction as a bidirectional (nondirectional) connection: If predator-j feeds upon prey-i, then the link is documented in the community matrix as $c_{ij} = 1$ and $c_{ji} = 1$. The community matrix also may include interactions such as competition, when two predators feed upon the same prey. This would also describe a situation where two species utilize the same nonfood resource, if one species parasitizes the other, or if they are engaged in a reciprocally positive relationship (mutualism).

The types of interactions represented by the organizing matrix (**[F]** or **[C]**) have a strong impact on the magnitude of derived parameters. It is critical to define the most appropriate matrix for the comparison of EIPs to FWs. Obviously, because **[C]** represents the matrix of a nondirectional digraph, it will have at least twice the number of links as the corresponding FW matrix, even if only predator-prey interactions are represented. Moreover, **[C]** often times include other interactions, as described above, further increasing links. In general, **[C]** is often used by ecologists (Briand 1983) to represent the upper bounds of connections in a network, as opposed to the strict representation of material and energy flows given by **[F]**. This has created some confusion in previous industrial network studies that have compared results of FWs represented by **[C]** to EIPs represented by **[F]** (e.g., Hardy and Graedel 2002; Dai 2010). Given that the focus of EIPs is on materials and energy transfers, one logically would express the relationships in an EIP as an FW matrix. Therefore, we take **[F]** as the appropriate matrix representation of all FWs useful for EIP comparisons as well.

Ecological Food Web Metrics

A wide variety of metrics have been developed to understand the link between structure and behavior of ecological systems (Fath and Halnes 2007; Bascompte and Jordano 2007). The structural measures and metrics used most frequently by ecologists, and which we apply to the EIPs here, are defined as follows.

Species Richness (N): the total number of species in a food web. This can be different from the number of species documented in the ecosystem given that species are often aggregated; one example is aggregation into "trophic species." Trophic species are defined as functional groups of taxa that share some set of predators and prey (Dunne et al. 2002b). Aggregation into trophic species is widely accepted among ecologists because it has been shown to reduce the methodological biases related to uneven resolution by the observer. It must be noted that ecologists will often refer to their aggregations of species as simply species, potentially misleading uninformed readers. Species richness is denoted here as N for nodes, to emphasize that the species from the original ecosystem may have been aggregated. The size of the FW matrix **[F]** is always $N \times N$.



$$\mathbf{F} = \text{prey} \begin{array}{cc} & \text{predators} \\ & \begin{array}{ccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \end{array} \\ \begin{array}{c} 1\\2\\3\\4\\5\\6\\7\\8\\9\\10\\11\\12\\13 \end{array} & \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&1&0\\ 1&0&1&0&0&0&0&0&0&1&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&1&0\\ 0&0&0&1&1&1&0&0&0&0&0&0&0\\ 1&0&0&0&0&0&0&0&1&0&0&0&1\\ 0&0&0&1&0&1&0&0&0&0&0&0&0\\ 0&0&0&1&1&1&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&1&0&0 \end{bmatrix} \end{array}$$

Figure 1 Left: a food web of a hypothetical ecosystem with species numbered. Right: a food web matrix; $f_{ij} = 1$ represents a unidirectional link between prey (i) and predator (j) and a zero represents no link.

Number of Links (L): the number of direct links between species in a web. Represented by the number of nonzero interactions in **[F]**, as shown by equation (1).

$$L = \sum_{i=1}^{m} \sum_{j=1}^{n} f_{ij} \tag{1}$$

Linkage Density (L_d): the ratio of links to species in **[F]** (equation (2).

$$L_d = {}^{L}\!/_{N} \tag{2}$$

Prey (n_{prey}): a species eaten by at least one other species (Schoener 1989); represented by the number of nonzero rows in **[F]** (equations (3) and (4).

$$f_{row}(i) = \begin{cases} 1 \text{ for} \sum_{j=1}^{n} f_{ij} > 0 \\ 0 \text{ for} \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{3}$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i) \tag{4}$$

Predator ($n_{predator}$): a species that eats at least one other species (Schoener 1989); represented by the number of nonzero columns in **[F]** (equations (5) and (6).

$$f_{col}(j) = \begin{cases} 1 \text{ for} \sum_{i=1}^{m} f_{ij} > 0 \\ 0 \text{ for} \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{5}$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \tag{6}$$

Prey-to-Predator Ratio (P_r): the ratio of prey to predators (equation (7).

$$P_r = {}^{n_{prey}}\!/_{n_{predator}} \tag{7}$$

Generalization (G): the average number of prey eaten per predator in **[F]** (equation (8).

$$G = {}^{L}\!/_{n_{predator}} \tag{8}$$

Vulnerability (V): the average number of predators per prey in **[F]** (equation (9).

$$V = {}^{L}\!/_{n_{prey}} \tag{9}$$

Connectance (c): the number of realized direct interactions in a web divided by the total number of possible interactions, equation (10). If one forbids cannibalism, then the denominator is the fraction of nonzero off-diagonal elements in **[F]**, equation (11).

$$c = {}^{L}\!/_{N^2} \tag{10}$$

$$c = {}^{L}\!/_{N(N-1)} \tag{11}$$

Cyclicity (λ_{max}): a measure of the strength and presence of cyclic pathways in the system (Fath and Halnes 2007; Allesina et al. 2005). Cyclicity is obtained by finding the maximum real eigenvalue of a network's structural adjacency matrix **[A]**, where the adjacency matrix is the transpose of the FW matrix: $[\mathbf{F}]^{T} = [\mathbf{A}]$. Cyclicity may take a value of either 0, indicating no internal cycling is present; 1, indicating simple internal cycling is present; or greater than 1, indicating increasing complexity and presence of internal cycling.

With respect to cyclicity, the dynamics and stability of FWs are significantly influenced by nutrient recycling and decomposition (McCann 2012). Detritivores and decomposers are the organisms (e.g., earthworms, fungi, and bacteria) that

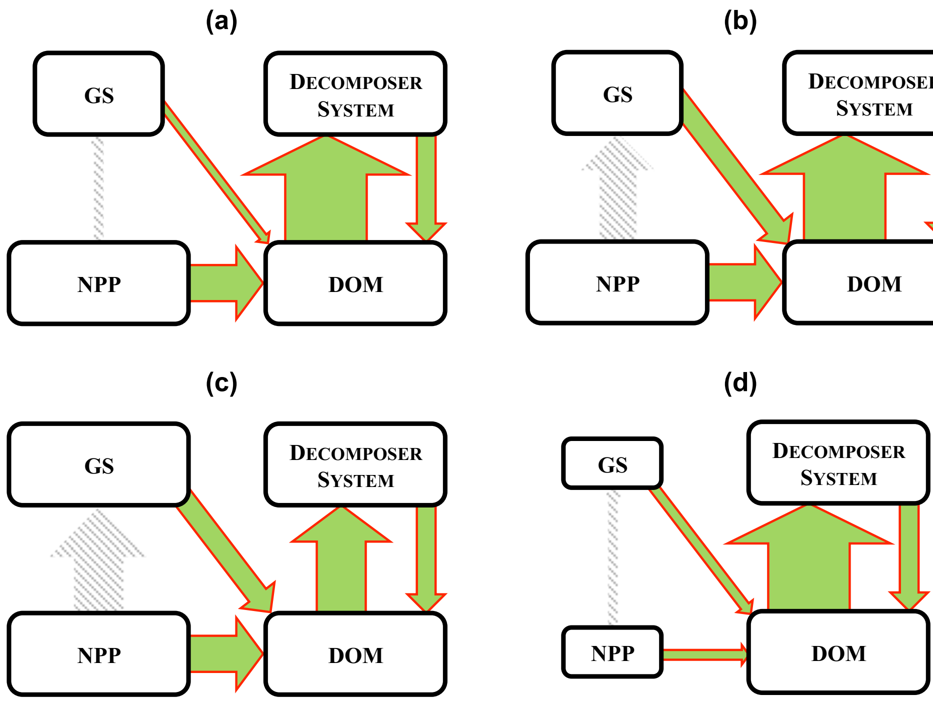


Figure 2 Proportional energy flows between subgroups in four ecological cycles: (a) forest; (b) grassland; (c) plankton community in the sea; and (d) the community of a stream or small pond. The relative size of the boxes and arrows are proportional to the relative magnitude of the compartments and flows. NPP = net primary production; GS = grazer system, also known as the live consumer system; DOM = dead organic matter; Decomposer System = decomposers and detritivores. Adapted from Townsend and colleagues (2008) with permission of John Wiley & Sons, Inc. Copyright © 2008 by John Wiley & Sons, Inc.

are responsible for the decomposition of dead organic matter (DOM) and the distribution of nutrients to the system. This process creates a fixed cyclic structure, causing these organisms to sometimes be referred to as the "recyclers of the biosphere." The detritivores and decomposers as a group are fundamentally different from any other functional group present—they allow energy to flow unrestricted to any location in the system and process a large percentage of the total energy. Figure 2 shows the relative importance of different pathways in four ecological cycles through the relative size of the boxes and arrows representing the compartments and flows in each system. The decomposer/detritivore pathway may see 5 times the energy flux as other pathways, reaffirming the idea that this functional group is invaluable (Townsend et al. 2008). Despite the importance of flows to and from this component (Husar 1994; Fath and Halnes 2007; Halnes et al. 2007; Allesina et al. 2005; Moore et al. 2004), FW analyses do not always include detrital flow. This is why we follow the method of Fath and Halnes (2007) of including missing connections to and from explicitly listed detritus species in some of the FWs taken from the 1983 collection by Briand (Briand 1983). The FWs that were modified are also included in their original format, all of which may be found in supporting information S3 on the Web. Modified FWs have been labeled with an M, signifying that it was modified from its original reference state to include links to the detritus.

Analyses and Comparisons of Eco-Industrial Parks and Ecological Food Webs

We can create FW matrices for industrial networks by substituting an industrial facility for each species and an industrial resource flow for each link, resulting in a conservative industrial interpretation of an FW. The FW matrices for the 48 industrial parks are listed in supporting information S2 on the Web. The ten ecological metrics, as defined above in equations (1) to (11), were then calculated for each.

The process for creating an FW matrix for an EIP is shown in figure 3 for the Kalundborg EIP. The structure of the exchanges within the EIP as of 2010 has been translated into ones and zeroes. The 17 companies within the Kalundborg EIP become species 1 to 17, and the links documented between them become the exchanges.

Calculated metrics for the 48 collected EIPs (*EIP*) are plotted in figure 4 alongside all 144 collected ecological FWs (*FWA*). Owing to the previously discussed importance of the detritivores and decomposers in the cycling of materials and energy, the impact of cannibalistic interactions on the structure, and the shift in collection and documentation techniques among ecologists in the early 1990s (Polis 1991; Cohen et al. 1993), the FWs have been further sorted into those with and without detritus and cannibalism and those collected before and

To Process # -- Consumer

From Process # -- Producer		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Farms	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inbicon	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Lake Tisso	3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Statoil	4	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0
Fertilizer Industry	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kara/Noveren	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cement Industry	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gyproc	8	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Nickel Industry	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DONG Energy	10	0	1	0	1	0	0	1	1	1	0	1	0	0	0	1	0	1
Kalundborg Forsyning	11	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0
Wastewater Treatment Plant	12	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Purification Plant	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
RGS 90	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Novo Nordisk & Novozymes	15	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Pig Farms	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fish Farms	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3 Food web matrix representation of the Kalundborg eco-industrial park as of 2010. (Another representation of the exchanges within Kalundborg may be found in figure 5.)

after 1993 (*FWD*, *FWND*, *FWC*, *FWNC*, *FWPre*, and *FWPost*, respectively).

Figure 4 plots the information using box plots, which highlight the median value for each data set, as well as the overall distribution of the data and intervals from which a difference between medians at the 5% significance level may be concluded. The triangles represent intervals for which two medians may be said to be statistically different at the 5% significance level if the intervals do not overlap. The crosses in the plots are the outliers in each data set, defined as such if they are larger than $[q_3 + 1.5(q_3 - q_1)]$ or smaller than $[q_1 - 1.5\ (q_3 - q_1)]$, where q_1 and q_3 are the 25th and 75th percentiles. The intervals are calculated as $[q_2 \pm 1.57(q_3 - q_1)/\sqrt{}\ (n)]$, where q_2 is the 50th percentile and n is the number of data points in the set. Table 1 summarizes statistical differences in median values between the *EIP* data set and the *FWA* data set for each of the metrics plotted in figure 4.

General Patterns and Comparisons

Figure 4 and table 1 show trends across ten FW metrics for FWs and EIPs. The results indicate that the two differ among a number of metrics that describe form and structural patterns. Table 1 shows that median values for the EIPs versus the FWs can be said to be statistically different with 95% confidence for the metrics species number, links, linkage density, prey, predators, prey-predator ratio, vulnerability, and generalization. The differences highlight that the structure of EIPs and FWs are dissimilar, which translates into differences in network functions. Also seen here is that structural metrics are sensitive to the types of interactions represented (specifically, cannibalism and detritivores). It follows that other metrics not investigated here may also be affected by the types of interactions represented in a system.

EIPs, in comparison with FWs, were found to be smaller networks with a lower density of connections (N, L, L_d). The number of species and links define the network, whereas the density of these linkages and their ratio to number of connections structurally possible define the structure. The lower degree of connectivity in EIPs translates, as expected, to lower numbers of prey and predators composing the system (n_{prey}, $n_{predator}$,). The density of linkages per prey (V) and predators (G) in the system, 40% to 70% lower in EIPs than FWs, tells us each predator in an EIP exploits less prey (G), and prey are consumed by fewer predators (V). The ratio of prey to predators (P_r) in EIPs is approximately 20% lower than that in FWs. The lower densities of links, prey, and predators indicate that each component in an EIP transfers material to and from a smaller number of components than in an FW.

Cyclicity, a measure of internal cycling often found in the form of recycling, is representative of efficient materials and energy use in the system. Given that energy and materials savings in EIPs are highly dependent on the successful cycling of waste and by-products, cyclicity is an important metric. Differences in the metric cyclicity, with the median value for EIPs falling 55% below that of FWs, highlight the less-complex internal cycling present in the structure of EIPs, as compared food webs. A value of cyclicity equal to 1 is indicative of one simple cyclic loop that all connected components participate in; many EIPs here fall into this category. A number of the EIPs show a cyclicity of zero, however, meaning no cyclic structure is present in the system. The median value of cyclicity for FWs is more than 1 and 0.5

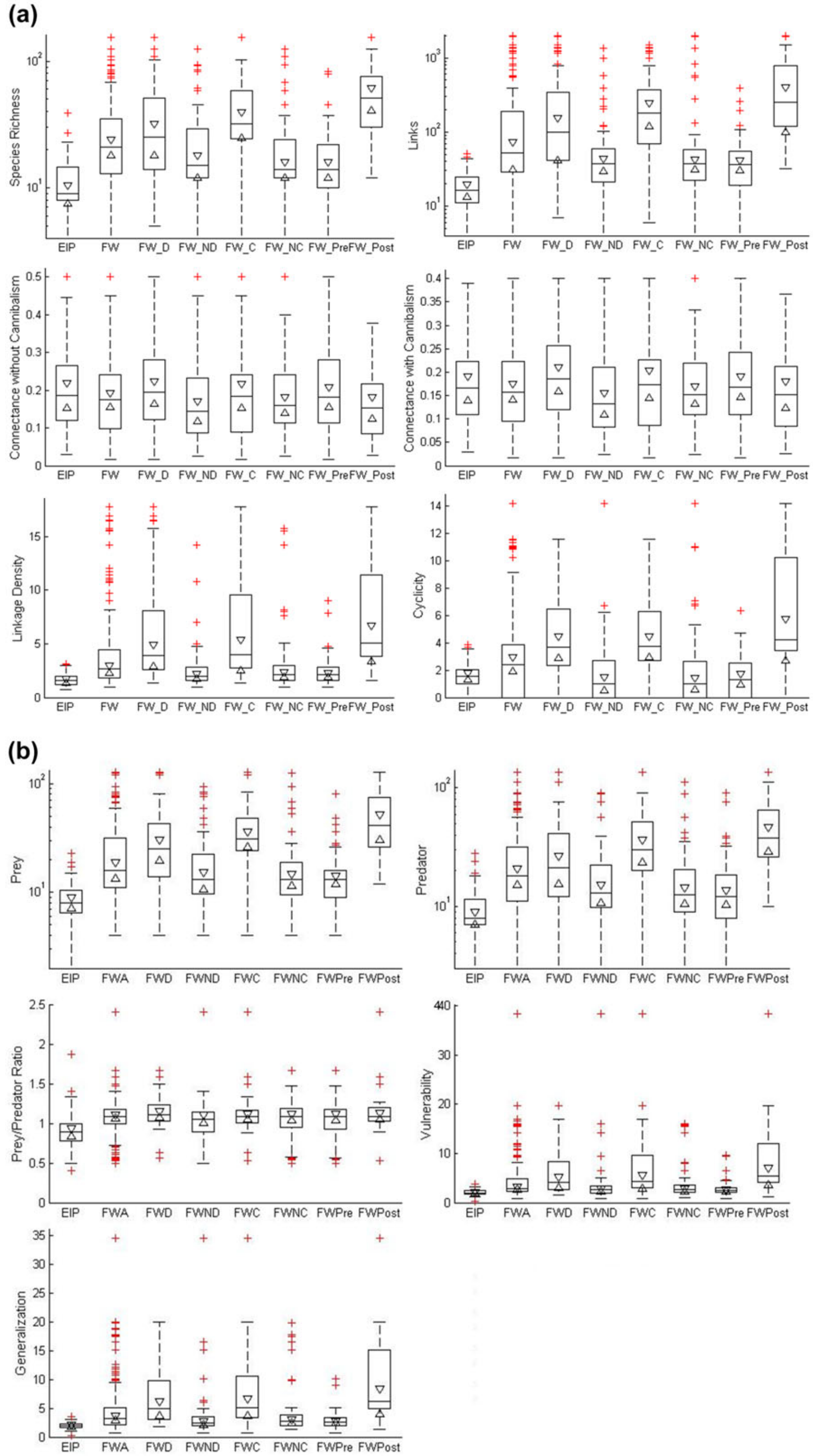


Figure 4 Ten ecosystem metrics (with a variation on one of the ten) calculated from the food web matrix [**F**] as applied to eco-industrial parks (*EIP*) and food webs (*FWA*) data sets. The food web data set (*FWA*) is then organized into those with a documented detritivores component (*FWD*) and a documented cannibalism interaction (*FWC*); those without are (*FWND* and *FWNC*), respectively. (*FWPre* and *FWPost*) are those food webs collected before 1993 and after 1993, respectively. Figure 4(a) shows the following five metrics: species richness (*N*); links (*L*); connectance (*c*)—calculated both with and without cannibalism; linkage density (L_D); and cyclicity (λ_{max}). Figure 4(b) shows the following five metrics: prey (n_{prey}); predator ($n_{predator}$); prey-to-predator ratio (P_R); vulnerability (*V*); and generalization (*G*).

Table 1 Summary of figure 4 showing medians and notch intervals for ten food web metrics as applied to the EIP and FWA data sets.

Metric	*Data Set*	*Median*	*Notch interval*	*Statistically different at 5% significance level?*
Species richness	*EIP*	9	[7.53, 10.5]	Yes
	FWA	21	[18.3, 23.9]	
Links	*EIP*	17	[13.4, 19.6]	Yes
	FWA	52	[31.1, 72.9]	
Linkage density	*EIP*	1.55	[1.39, 1.71]	Yes
	FWA	2.67	[2.32, 3.01]	
Connectance with cannibalism	*EIP*	0.166	[0.140, 0.192]	No
	FWA	0.158	[0.141, 0.174]	
Connectance without cannibalism	*EIP*	0.186	[0.154, 0.219]	No
	FWA	0.175	[0.156, 0.193]	
Prey	*EIP*	8	[7.09, 8.91]	Yes
	FWA	16	[13.3, 18.7]	
Predators	*EIP*	8	[6.98, 9.02]	Yes
	FWA	18	[15.3, 20.7]	
Prey-predator ratio	*EIP*	0.889	[0.838, 0.940]	Yes
	FWA	1.08	[1.06, 1.11]	
Vulnerability	*EIP*	2	[1.84, 2.16]	Yes
	FWA	2.92	[2.59, 3.25]	
Generalization	*EIP*	1.91	[1.77, 2.07]	Yes
	FWA	3.27	[2.89, 3.66]	
Cyclicity	*EIP*	1.56	[1.33, 1.79]	Yes
	FWA	2.41	[1.91, 2.92]	

Note: If the notch intervals do not overlap, then the median of the two data sets may be said to be statistically different with 95% confidence. *EIP* = eco-industrial park data set; *FWA* = food web data set encompassing all 144 food webs.

times larger than EIPs, indicating a much more complex set of pathways. The internal cycling in FWs is strongly influenced by the presence of decomposers as well as cannibalism, which creates a self-loop.

So, we see that EIPs generally appear to be less connected than FWs. The types of interactions present (cannibalism, decomposers, competition, and so on) influence the magnitude of these differences; EIPs fall closer to those FWs without cannibalism and detrital interactions, suggesting that the failure to include such functional roles in EIPs is, at least partially, responsible for their lower cyclicity relative to FWs. These specialized interactions were previously dismissed by FW theorists; a lack of documented cannibalism and decomposers was detailed as one of the four substantial problems in FW ecology before the early 1990s (Polis 1991; Cohen et al. 1993). Changes in collection and documentation techniques since 1993 have resulted in a greater percentage of FWs documenting detrital and cannibalistic links (in the FW data set used here: 92% after 1993 vs. 26% before). The documentation of the specialized interactions of detritivores and cannibalism is likely the reason behind the large differences in median values of structural parameters (N, L, L_d, n_{prey}, $n_{predator}$, V, G) in FWs collected before and after 1993.

Although the general relationships in figure 4 and table 1 are instructive, ecologists have noted that values of some metrics are clustered or display particular patterns with species number (Schoener 1989; Briand and Cohen 1987; Cohen 1977, 1978; Cohen and Briand 1984; Warren 1990). One of these is that linkage density (L_d) does not vary with species richness (N) (Cohen et al. 1990; Warren 1990); thus, we expect a linear relationship between N and L. We confirm this for FWs (*FWA*), as well as for EIPs (*EIP*). Linear data fits for the two data sets highlight that the EIPs tend to have significantly fewer links per species than FWs of similar size. The increase of L with N is significantly greater for FWs than for EIPs; the slope for the linear fit of *EIP* data is 1.4 while for *FWA* data it is 12, almost 9 times higher. This trend is most apparent at around 30 species, where the relationship of L to N appears to diverge. An analysis of covariance analysis of L as a function of N with web type as the classification variable confirms these observations; for the entire model $r^2 = 0.73$ ($F_{3,187} = 183.7$; $p < 0.001$), with significant effects of N (the regression variable), web type, and their interaction ($F_{1,187} = 6.22$, $p < 0.001$; .054, $F_{1,187} = 1.94$, $p = 0.054$; $F_{1,187} = 2.67$, $p < 0.01$; respectively). We cannot comment on the trend between N and L beyond $N = 30$ for the EIPs, owing to the fact that we only have one EIP example with more than 30 companies.

Discussion

Determining the causal differences that prevent industrial systems from functioning like natural systems is necessary in order to evaluate and understand how ecological principles may inform the organization of industrial systems. The EIPs investigated here are not constructed and, consequently, do not function like their food web analogs, supporting previous conclusions (Reap 2009). This more thorough understanding becomes a potential source of insight regarding how to structure and analyze industrial system organization.

Differences in Complexity

Most structural parameters investigated here show that EIPs are less complex than their ecological counterparts. Those metrics that normalize for network size show that the limited complexity of EIPs, relative to FWs, appears to be unrelated to scale. Compared to their FW analogs, each company in an EIP has fewer connections to other companies in the network (L_d) and there are more companies that use resources and energy (predators) than there are companies within the network that provide those resources and energy (prey), as seen in the prey-to-predator ratio (P_r). The later observation highlights that EIPs tend to have one or a few companies acting as the sources of materials and energy for the rest of the members. Consequently, the average numbers of links per prey (V) and per predator (G) are significantly lower in EIPs than FWs.

Connectance was found here to be the only FW metric in the group that did not behave as expected (i.e., that FWs would outperform the EIPs was hypothesized), similar to what was found by Hardy and Graedel (2002). No statistical difference in median connectance values between *EIP* and *FWA* was found, calculated from both equations (10) and (11); the median values for EIPs are actually slightly higher. Looking at equation (10), we see that N is squared in the denominator. Consequently, a network with more actors will have a significantly smaller connectance than a network with few actors, even if its linkage density is much larger. For example, a network with 8 actors and 20 links will have a more favorable connectance than a network with 80 actors and 200 links. Thus, FWs, with their large N values, are essentially handicapped in comparison with EIPs when using connectance. To fairly make comparisons, we must focus on networks with similar numbers of species (N). When we focus on those FWs of similar size to the EIPs ($N < 30$), the median connectance for FWs (with cannibalism) is greater than EIPs, increasing from 0.158 to 0.178. Additionally, focusing on FWs collected after 1993, the median connectance (with cannibalism) increases yet again to 0.208. Connectance is potentially an important design parameter given that it can tell us about the overall structure, complexity, and robustness of the system (Dunne et al. 2002a, 2002b). Thus, it is important to note that comparisons using connectance must focus on networks of similar sizes.

Differences in Functional Roles

Differences between EIPs and FWs also reflect the fact that important functional roles may not be represented in EIPs. FW ecologists have long stressed the profound impact of detrital energy pathways on many facets of ecological systems (Fath and Halnes 2007; Husar 1994; Korhonen 2001). Over half of all the material in a FW is connected to a decomposer-type species, which recycles unused material and returns it to the system. Abundant recycling of energy and materials is characteristically found between the components of mature ecological systems, resulting in relatively small volumes of new inputs to the system (Odum 1969). Less than 10% of the annual net production in a mature forest system is consumed in a living state; most is used as dead matter through delayed and complex pathways (Odum 1969). Cannibalism is also abundant in FWs (Polis 1981; Woodward and Hildrew 2002) and has been shown to have a strong influence on the dynamics and structure of communities and entire ecosystems (Persson et al. 2003).

The EIPs here fall closest to those FWs without detrital or cannibalistic components (*FW NoDetritus* and *FW NoCannibalism* in figure 4). EIPs also more closely resemble FWs collected before 1993 (*FW Before 1993* in figure 4), which is most likely owing to the infrequency of detrital and cannibalism documentation preceding the shift in FW collection methods. It is unlikely that high cyclicity values can be achieved in EIPs without these functional roles, which would seem to suggest that EIP designers should incorporate analogous interactions in industrial networks to achieve more connectivity and greater cycling. As noted, species that consume DOM are responsible for FW pathways that include all other species and feed back into all other available loops. Even limited connections to a component such as this in an EIP would dramatically increase connectivity and thereby efficiencies.

Cannibalism, from a purely mathematical viewpoint, allows for N additional linkages in the system. This gives a higher linkage density and connectance than if cannibalism is absent. Analogous interactions for cannibalism in an industrial setting are possible; it is perfectly plausible that a company in an EIP could use its own by-product or even recycle its own products that have quality defects into new products. We have not observed these interactions specifically documented in the literature to date; however, this may be an artifact to the lack of importance placed on these interactions in the FW literature when EIPs were first investigated. Including them in the future will provide a much better understanding of the key components of ecosystem structure that have evolved to make them ultimately sustainable (Jelinski et al. 1992).

Eco-Industrial Park Performance Comparisons

The 48 EIPs listed in tables S1-1 and S1-2 in the supporting information on the Web were ranked in terms of their success in reaching a biologically inspired state using cyclicity (λ_{max}), linkage density (L_d), the prey-predator ratio (P_r), generalization (G), and vulnerability (V). The other five metrics used in this article were not selected because they are all affected by network size (species number, links, prey, predator, and connectance). The results group the EIPs into three classes: those EIPs with $\lambda_{max} > 1$, representative of complex internal cycling (*Type 3*); those with $\lambda_{max} = 1$, meaning that simple internal cycling is present (*Type 2*); and, finally, those EIPs with $\lambda_{max} = 0$, meaning that no internal cycling is present in the system (*Type 1*). The top performers are seven EIPs with a cyclicity greater than 3,

Table 2 Top seven performers in the EIP data set compared to median values for 50 food webs that were collected after 1993

				λ_{max}	L_d	P_r	G	V
	FWs post-1993 median values			4.24	5.04	1.09	6.18	5.34
Top seven EIPs	(Reap 2009)	Proposed	The Green Triangle	3.87	3.13	1.14	3.57	3.13
	(Debref 2012; Chauvet 2012)	Exists	Pomacle-Bazancourt	3.70	2.67	1.00	3.00	3.00
	(Reap 2009)	Failed	AES Thames EIP	3.53	3.00	1.00	3.00	3.00
	(Abuyuan et al. 1999)	Proposed	Renova (RRP)	3.39	3.00	1.00	3.00	3.00
	(Reap 2009)	Proposed	Clark Special Economic Zone	3.34	2.55	0.890	2.68	3.00
	(Frosch et al. 1997)	*Exists*	Copper Industry Web	3.12	3.07	0.92	3.54	3.83
	(Cote 2010)	*Exists*	Kytakyushu RRP	3.00	1.55	0.80	1.70	2.13

Note: The five metrics used in ranking the success of the EIPs are cyclicity (λ_{max}), linkage density (L_d), prey-predator ratio (P_r), generalization (G), and vulnerability (V).
FWs = food webs; EIP = eco-industrial park; RRP = resource recovery park.

exhibiting the most complex internal cycling in the group; these top EIPs are highlighted in table 2.

The top seven EIPs listed in table 2 have one or more detritus-type actors. We define a detritus-type actor for an EIP as an actor that is of the type waste treatment (i.e., composting), recovery and recycling (i.e., repair, remanufacture, reuse, resale), or agriculture (i.e., farm, zoo, landscaping, greenhouse, golf course). Additionally, to qualify as a detritus-type actor, there must be at least one link entering and leaving said actor. This last criterion is based on the fundamental job description of a detritus/decomposer in an FW and ensures that the detritus-type actor is an active participant of the EIP. It is interesting to note that over half, four of the seven top EIPs, have some form of composting- or agriculture-type actor. The EIPs in this top group tended to have a larger-than-average linkage density as well.

The presence of active recyclers in the system results in complex cycling, even when fewer connections exist (a lower linkage density). The lowest EIP in the top group, Kytakyushu Resource Recovery Park (RRP) in Japan, has a low linkage density and prey-predator ratio in comparison to the rest of the group, while still maintaining a high cyclicity. The FW matrix for Kytakyushu (found in the tables of supporting information S2 on the Web), shows that all of the interactions in the system are to and from only one of the eleven actors: the resource recovery facility, which is the acting detrital species. Clark Special Economic Zone, ranked fifth in this top group, also has a lower linkage density, as compared to a majority of the top EIPs. Of the 51 links between the 20 actors in Clark, those actors that saw the most connections were the five composting/processing/recovery facilities; 84% of the total links in the system passed through these detrital-type actors. The Kytakyushu RRP has 100% of the total links in the system passing through its detritus-type actor.

Kalundborg surprisingly ranks in the bottom half of the *type 2* EIPs, those exhibiting only basic internal cycling. Comparing Kalundborg to Pomacle-Bazancourt, the top ranking working EIP, figure 5 highlights the level of participation of the detritus actors, outlined in red, in each system. All except one of the 15+ cycles in Pomacle-Bazancourt involve the two detritus actors. Kalundborg also has two detritus actors, but only one detritus actor participates in merely two of the three existing cycles. So, Kalundborg has (1) far fewer cycles and (2) detritus actors that are disengaged from the majority of the system, whereas those EIPs in the top performing group have a majority of their total links involved in a cycle and highly involved detritus actors. These observations reinforce the observations of ecologists, who posit that the central value of decomposers lies in their ability to link various components that otherwise do not interact.

Six EIPs are ranked as *Type 1* that exhibit no internal cycling. These EIPs are characteristic of a cyclicity value of zero, as well as low linkage density. Connecticut Newsprint ranks the lowest of all the EIPs. Interestingly, it does have a composting and a recycling component, but these actors fail to provide any benefits with regard to structure; they each only have one connection with the rest of the system. Triangle J located in North Carolina, another EIP in this bottom group, has a wastewater treatment plant, which interacts with three other actors; however, similar to Connecticut Newsprint, it, too, fails to be an active enough participant to have an impact on the internal cycling. So, we see that it is not enough to simply have a "detrital" component in an EIP; it must be an active participant in the system in order to create meaningful cycles of materials and energy. An EIP with no internal cycling seems contrary to what one expects of a bio-inspired industrial network given that one of the most influential and identifying characteristics of biological networks is the prevalence and importance of materials and energy cycling within the system. Should nonzero cyclicity be a requirement for the designation of an industrial network as an EIP? This is something that may potentially be considered in the future for EIP designation, similar to a Leadership in Energy and Environmental Design certification system.

Appropriate Ecological Network Analyses for Eco-Industrial Parks

The analysis presented here suggests that ecological network analyses provide useful methods for future attempts to benchmark EIPs and examine their structural properties. The relevant issues are: What calculations should be performed, and what ecological data provide appropriate comparisons?

First, we propose the use of a FW matrix **[F]** for EIP-FW analyses and comparison, given that using a community matrix

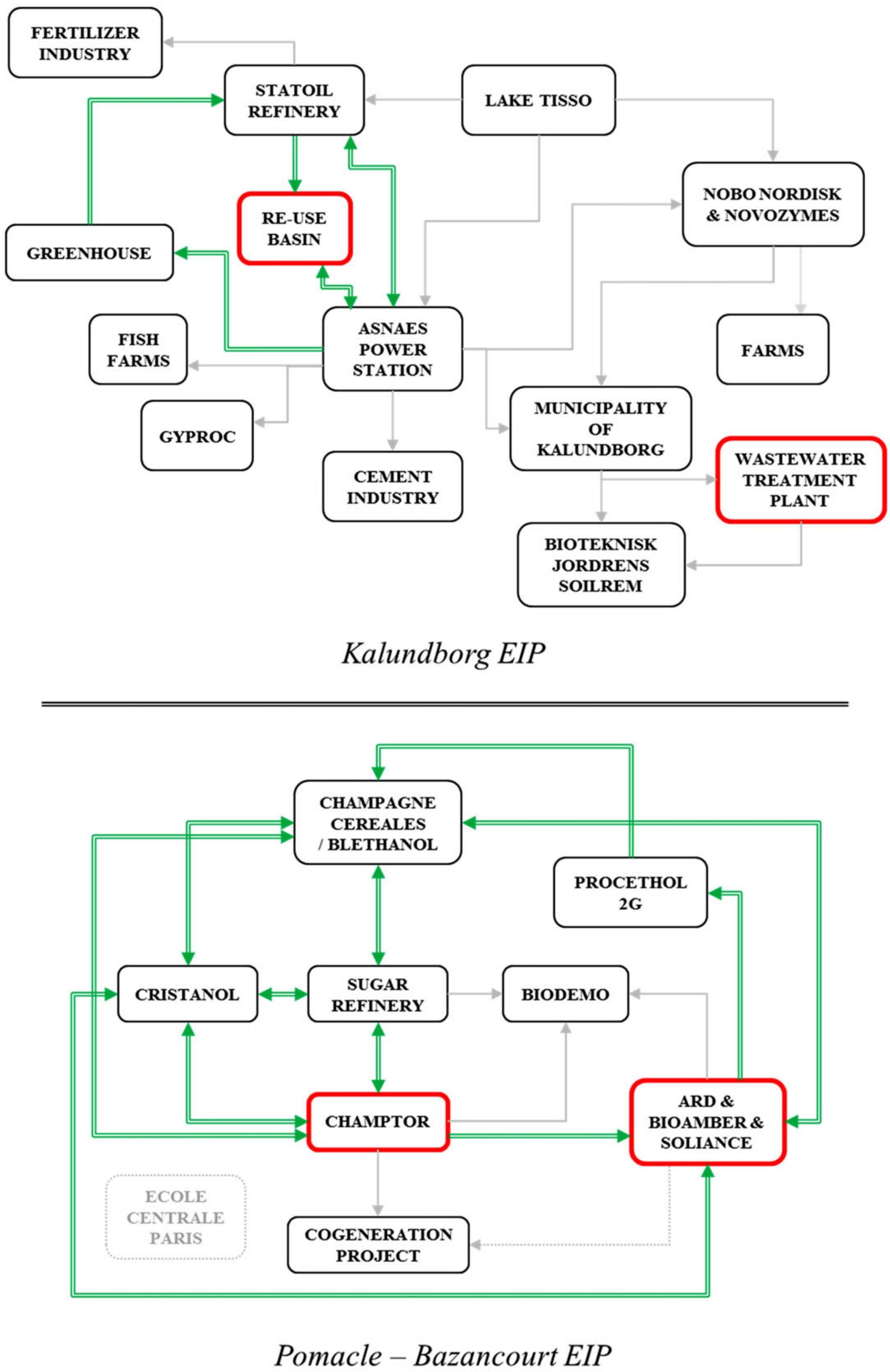


Figure 5 Comparison of the internal cycling of materials and energy within the Kalundborg and Pomacle-Bazancourt eco-industrial parks (EIPs). Green double line arrows represent linkages that participate in a cycle; gray links do not. Actors highlighted thickly in red are the acting detritus of the EIP.

[C] is not appropriate. As described in the *Ecological Network Analysis* section above, the community matrix documents all interactions as bidirectional, double counting each interaction and further increasing the number of linkages documented. The community matrix also includes competitive interactions between species. From a material and energy flow perspective, only a direct relationship (who eats whom) seems relevant in industry. Including competition in ecological matrices was originally used to measure the complexity of interactions and not provide insights into material flow. Moreover, most industry interactions are specific, so that even if companies A and B both receive flow from company C, they will receive flows of different substance/quality and therefore not be in competition with each other. This makes it more difficult to analogize competition into an EIP setting.

We also suggest including the potential for cannibalism, in view of the ecological significance of this interaction and its straightforward analogy to industrial processes. Thus, future comparisons of connectance should use equation (10), rather than equation (11) as many previous analyses have done (Briand 1983; Hardy and Graedel 2002; Reap 2009). For example, Hardy and Graedel analyzed 18 industrial parks and organized them using a community matrix [C] (Hardy and Graedel 2002). Median values for connectance, calculated without cannibalism from the community matrix, were found to be 0.456 for EIPs. This was compared to a median value for FWs found by Briand of 0.423 (Briand 1983). Hardy and Graedel do not include any competitive interactions in their EIPs (Hardy and Graedel 2002); these interactions, however, *are* included in the ecological data set by Briand that they use for comparisons (Briand 1983). As such, the connectance values for FWs and EIPs are not compared accurately, making previous conclusions somewhat tenuous.

A final consideration is which ecological data sets provide the most accurate depiction of systems that can act as a good benchmark for EIPs. Owing to the nature of the changes made in the early 1990s to the collection and documentation of FWs, and the strong impact explicitly including cannibalism and detrital interactions has on common metrics, we propose that the FW data set "*FWPost*" be used for EIP comparisons. The FWs in this collection are a much more accurate representation of the ecological networks and how the species in such a network interact. They are much larger networks with higher diversity and a higher density of linkages. They also show a significantly more complex cycling structure than those FWs that were collected before 1993. Although using this data set gives an even higher benchmark for EIP designers to reach for, it will provide more realistic appraisal and, hopefully, allow for richer insights into how to design more sustainable industrial systems.

Conclusions

Using traditional and newer FW metrics and a more ecologically correct understanding of how they are calculated, we have shown that current EIPs follow some properties of biology's naturally sustainable systems through their characteristic symbiotic relationships, but, overall, these networks still have a long way to go to meet the resilient and efficient properties of nature's long maturing networks. At best, current EIPs mimic those FWs lacking cannibalism and decomposers, two very important components in creating the desirable cyclical structure of FWs. We propose here that, for comparisons with EIPs, only FWs collected from 1993 and on should be used, given that they are much more likely to include cannibalism and decomposers. We also propose that an FW matrix is used to calculate metrics for both EIPs and compared other FWs. Going forward, we urge those wishing to use FWs as analogs to industrial systems to carefully consider the interactions represented in both systems in order to make appropriate comparisons. The EIP data set presented in this article is more than twice the size and far more detailed than those offered by previous publications. Continuing the collection of EIPs, especially those with greater than 30 companies, would give further insight. Additionally, expanding the EIP data set to include flow information, such as magnitude and environmental importance, would allow for the use of additional FW metrics, which give a more balanced summary of the network. Flow magnitude information is exceedingly difficult to obtain, however, for both industrial networks as well as for FWs. This is hopefully an issue that will be resolved as the successes and positive impacts, both environmentally and financially, of designing industrial networks to mimic ecological FWs become more obvious.

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Note

1. The term eco-industrial park (EIP) is used here to refer to colocated, interacting industries. The interacting industries may be in a formal industrial park or colocated without an element of common management; the latter is often referred to as an industrial symbiosis complex.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information contains two tables. The first table (table S1-1) contains a data set of 48 EIPs collected through literature reviews and Internet searches. The second table (table S1-2) ranks the data set of table S1-1 according to the nondimensional ecological metrics cyclicity, linkage density, prey-to-predator ratio, generalization, and vulnerability.

Supporting Information S2: This supporting information provides structural matrices for the 48 EIPs used in the main article.

Supporting Information S3: This supporting information provides the data used to create the FW averages used in the main article.