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An Island Approach to Industrial Ecology: Towards Sustainability in the Island Context

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ABSTRACT *Many fields of study have employed geophysical islands in experimental design with a great deal of success. An island is a closed and bounded system in many respects and presents a manageable unit of study. The island microcosm has been the basis for significant advances in areas such as evolutionary biology, ecosystem ecology and physical anthropology. The same properties that make islands so useful to scientists present island populations with pressing sustainability challenges of limited resource availability and natural carrying capacity. This paper discusses the characteristics of the island context to show the severity and immediacy of these challenges. Based on this discussion, it is apparent that new approaches are needed to address sustainable development on islands. Island systems and the study of industrial ecology, which examines industry embedded within the finite natural environment, have much to gain from one another in this respect. Several industrial ecology case studies, primarily drawn from research in Puerto Rico, are presented to illustrate the compatibility of islands as a study unit in this field. Industrial ecology presents new solutions to the challenges of sustainable island development, while well-defined island systems offer a unique opportunity for the approach of industrial ecology.*

Introduction

Islands dot the oceans of the earth and conjure numerous associations ranging from autonomous nation states to tropical tourist paradises to isolated outposts of civilization. Excluding Greenland, islands have a combined land area of about 7 700 000 km^2 or about 5% of the Earth's surface (Towle, 1985). Many fields of study have employed islands to advance human knowledge in the natural and social sciences with a great deal of success. The Galapagos Islands inspired Charles Darwin and Alfred Wallace to create the framework of evolutionary biology almost 140 years ago. Ecosystem ecologists Robert H. MacArthur and

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Edward O. Wilson developed islands as natural experimental models with their *Theory of Island Biogeography* (1967). Physical anthropologists have continually returned to islands as microcosms for the study of human behaviour (for example Kirch, 1997). Systems analysis of islands had great advances with UNESCO's Man and the Biosphere program in the 1970s studying the island systems of Hong Kong (Boyden, 1979), Fiji (Brookfield, 1980) and Gotland, Sweden (Zucchetto & Jansson, 1985).

The Man and the Biosphere studies were the first to examine islands by investigating the dynamics of modern human societies and the natural systems in which they exist. This research began to paint a comprehensive picture of the interaction between humans and nature that otherwise would be a grandiose endeavour at a continental scale. The study of human interaction with nature leads to the more complex question of how societies should live within nature. Although islands have been associated with utopian schemes at least since the famous novel of Sir Thomas More, a more normative view of island system studies followed the Man and the Biosphere work. Dolman *et al.* suggested that islands could be approached as a laboratory for alternative development strategies that addressed self-reliance (1982, cited in Towle, 1985).

Islands are systems that are closed and bounded in many respects and thus present a manageable unit of study for scientists. These same properties present island populations with the challenges of limited resource availability, tenuous resource security and limited natural carrying capacity. This paper argues that, while every human population faces these challenges, the need to find solutions for sustainable development is much more immediate for island systems. Industrial ecology is a growing field that examines industry embedded in nature in a systems approach. Island systems present an excellent opportunity for the application of the tools of industrial ecology, a field that focuses on proposing sustainable solutions to human development.

To advance the argument for studying island systems based on industrial ecology, the general characteristics of islands, sustainability and industrial ecology are first reviewed. Puerto Rico, an island in the Caribbean, is presented as an example of the modern technological society approaching the limits of environmental sustainability in an island system. A review of studies performed by the Yale University Center for Industrial Ecology are introduced, and some proposals for solutions to Puerto Rico's challenges based on industrial ecology are presented. Examples of other islands such as Iceland, Singapore and Nauru are used for comparative purposes. The discussion closes with some conclusions about the generalization of island studies in industrial ecology and the necessary link between industrial ecology and island systems.

The Island Context

Various island taxonomies have been created in an attempt to characterize the features of islands most pertinent to different forms of investigation (Fosberg, 1963; McElroy & de Albuquerque, 1990). While an island is generally perceived as a small unit of land surrounded by water, there is little consensus in the literature on island studies as to what precisely is an island. It is worthwhile, therefore, to discuss briefly the characteristics of islands and how these characteristics make islands interesting objects of study.

In an abstract sense, an island can be any discrete unit of land that is in some way bounded and isolated. Historically, islands were isolated by large expanses of water and took considerable time and effort to reach. Modern transportation has made most geographical boundaries permeable and increased the connectivity of islands to the rest of the world. The time and cost of transportation, however, still leaves islands isolated to some degree. Islands are also of limited size, although the upper limit to this characteristic is open to debate.[1] Regardless, the combined characteristics of boundedness, isolation and size act to limit resource availability on islands. It is worth noting that, from an ecosystem perspective, these characteristics open niches and decrease external competition (MacArthur & Wilson, 1967).

The island condition exists on a continuum based on size and connectivity, the latter characteristic dictating the extent to which an island is a closed system. In context of human resource needs, isolation from large centres of development restricts the ability of many islands to import electricity or fresh water. These resources often must be produced internally and used conservatively. Waste management, also, is limited based on island resources and assimilative capacities. However, many resources can be transported to islands including food, minerals, raw materials and fuel. Some islands even ship in their drinking water. Open migration enabled by modern transportation has permitted many human populations to grow and develop beyond the natural limits of endemic island resources.[2]

Frequently, islands are viewed as microcosms by those who study them, although the distinction is not always explicit *of what* an island is a microcosm. Islands are microcosmic in that they display the dynamics of competition for scarce resources and increasingly, the pressures and impacts of humans on the environment. Yet, islands are distinctive in their role as small systems affected by global-scale forces. Many unique problems arise where the closed, fragile island environment is coupled with open, global economic systems. Island geographers James McElroy & Klaus de Albuquerque write:

> Ecosystem stability is especially precarious where the small island system is resource intensive and anchored to a disproportionately large through-put system controlled by global forces and multinational actors. Swollen by foreign inputs and the profit motivations of far flung commercial interests and institutions, the economy develops a strong drive towards short-run exploitation as traditional resource use practices are upset by wage/price distortions and intrusive technology. (1990, p. 25)

An island is a system that is subject to internal dynamics as well as pressures from the larger system in which it exists. For environmental managers and planners, it is more appropriate to consider the *island context*, an isolated system with scarce resources, than the *island paradigm*, a bounded system with controlled conditions. The former offers a realistic perspective on how islands operate under the pressures of the human systems that cross their boundaries, while the latter is more appropriate for natural scientists who are less concerned with human influences.

Sustainability on Islands

The oft-cited Bruntland report set forth the notion of sustainability as a goal of intergenerational equity and resource management implicating both social and environmental concerns (WCED, 1987). While a wealth of definitions and principles has followed, Goodland & Daly (1996) offer three principles that sufficiently focus the sustainability discussion on environmental carrying capacity for the purpose of this paper. First, waste should not be released into the local environment at a rate that impairs future assimilation or ecosystem services. Second, renewable resources should not be used at a rate greater than they can be generated. Third, non-renewable resources should not be depleted faster than renewable substitutes can be developed. These principles provide objective goals for the perpetuation of human populations in resource-limited environments.

Studies of island anthropology have repeatedly shown a close, historical connection between environmental sustainability and human survival (Kirch, 1997; Erickson & Gowdy, 2000). The island context, therefore, brings sustainability concerns rapidly to the forefront of environmental management and planning. The size and isolation of islands limit the availability of critical resources, such as fresh water and fertile soil. Resource extraction and the release of by-products occur within a small space on islands, making environmental externalities more closely linked to their associated resource use. For resources that are supplied externally, resource security is a concern. An important resource may suddenly have its supply cut off or become prohibitively expensive, leaving the island without a well-developed, local alternative. In addition, islands with large, externally oriented economies often rely on a few, heavily weighted factors such as tourism, oil imports or tax incentives. Not only do these factors fail to account for the environmental constraints of the island system, but their sudden disruption can also leave an island vulnerable to serious resource shortages.

The island context shortens the planning horizon over which sustainability concerns become important. Petroleum supply provides an illustrative example. On the one hand consider a developed, continental nation, such as the USA. Faced with rising petroleum prices or diminishing external supply, the USA has several options: (1) decrease consumption; (2) extract more resources from internal reserves; (3) pursue greater petroleum use efficiency; or (4) develop an alternative resource to substitute for petroleum. The first options can be selected on a shorter time scale, while the latter options will require more time to become effective. Most likely, some combination of these strategies will be pursued, allowing the USA to soften the impact of limited external petroleum supplies. On the other hand, consider a developed, island nation such as Iceland facing a similar petroleum shortage. With few internal reserves developed, Iceland's near-term options in response to the shortage are limited, and it must choose among the more sustainable strategies: decreased consumption, increased efficiency or (renewable) substitution. The USA is currently considering extracting petroleum from internal reserves (in Prudhoe Bay, Alaska), while Iceland has made a commitment to replace externally supplied petroleum with internally generated hydrogen over the next 30 years (Arnason & Sigfusson, 2000). On a continental scale, sustainability concerns may rest 100 years or more in the future. In the island context, sustainability decisions are important over more immediate planning horizons.

It could be argued that this would not be the case if an island had an abundant supply of a key resource to support its economy. For example, Iceland would not be as willing to pursue alternative technologies if it had its own petroleum reserves. As a counterpoint to this argument, consider the case of Nauru, a small island in the South Pacific (Gowdy & McDaniel, 1999). The geology of Nauru bestowed the island state with a natural abundance of phosphorous, an important component of commercial fertilizers. Phosphorous mining began in 1907 and continued through the island's independence in 1968. Nauru used its natural abundance of a non-renewable mineral to drive its economic growth and development. Currently, nearly all of the phosphorous of Nauru has been mined, leaving the centre 80% of the island barren and devastated. Now the island must import nearly all of the goods, food and water consumed by its residents, who were completely self-sufficient only 100 years ago. The island may soon be uninhabitable as mining has made the climate hotter and dryer, lowered the water table, and eroded most of the island's topsoil. Failure to engage in sustainable planning has threatened the existence of this small island nation.

Environmental pollution also presents pressing sustainability concerns for islands. While it is beyond the scope of this discussion to consider all forms of environmental pollution in the island context, the example of a common type, greenhouse gases, is of particular interest. The negative impacts of local pollutants are apparent, and it would seem that emissions of global pollutants, like greenhouse gases, would not be a particular concern for islands. Yet, greenhouse gases have the potential to alter the global climate enough to bring about sea level rise through glacial melting. Islands are particularly vulnerable to inundation from sea level rise. They all have extensive coastal boundaries, and a large portion of an island's land mass and population exist near its coasts. Island nations have a great interest in curbing both their own greenhouse gas emissions and those of other nations.[3]

Limited resources, tenuous resource security and a fragile natural environment are inherent to the island context. Environmental sustainability may still be a long-term consideration for large, continental nations but represents a more pressing concern for islands. The need to bring human industry within the limits of environmental carrying capacity is of immediate importance for island systems.

Industrial Ecology

The field of industrial ecology considers industrial systems in concert with natural systems and strives to limit the environmental impact of industry. Since many environmental challenges can be traced to industry, industry should be a primary focus of efforts to increase environmental sustainability (Gibbs & Healy, 1997). Industrial ecology has a number of useful concepts to bring to bear on the sustainability concerns of island systems.[4] First is industrial symbiosis, which considers co-operation between traditionally separate industries in close geographic proximity (Chertow, 2000). This co-operation can come in several forms. Industries may physically exchange materials, water, energy or by-products. In addition, they may exchange information or co-ordinate planning to increase the collective efficiency of their operations. Facilitated regulatory permitting and joint marketing may also be features of industrial symbiosis. Industrial symbiosis works to increase the viability of the firms involved while addressing the demands of society for resource conservation and environmental protection. Biological symbiotic relationships act to increase connectivity and circulation of resources. Industrial symbiosis endeavours to extend these characteristics to industrial systems, thereby increasing their sustainability (Wallner *et al.*, 1996).

The most cited example of industrial symbiosis is that of the town of Kalundborg, Denmark, where there are some 20 resource exchanges involving an oil refinery, a power station, a gypsum board facility, a pharmaceutical plant, the Municipality of Kalundborg and other actors. The participants literally share ground water, surface water and wastewater, steam and fuel. They also exchange a variety of residues, such as ash and scrubber sludge from the power plant and sulphur from the oil refinery, that become feedstocks in other processes (Ehrenfeld & Gertler, 1997). Since this exceptional model can now be viewed over time, it is significant to note that the industrial symbiosis continues to evolve and adapt (Ehrenfeld & Chertow, 2002) and has significantly increased environmental and economic efficiency.[5]

Ehrenfeld & Gertler (1997) discuss several factors that are important to the success of an industrial symbiotic network. Any resource exchange must, of course, be technically feasible. Participants must be in close proximity to one another to facilitate exchanges and minimize handling and transportation costs of resource exchange. Feasibility is also higher for large, continuous waste streams rather than, for example, component wastes. Exchanges must be economically competitive with the resource flows that they would replace. Transportation costs, treatment costs, organizational costs or transaction costs may make the economics of exchange more or less favourable. Environmental regulations, especially those that deal with recycling materials that may be hazardous, must be flexible to allow exchanges to occur in an economical and efficient manner. Organizational culture also plays an important role (Jacobson & Anderberg, 2001). Key decision makers among the firms involved must have access to one another and share the motivation to pursue symbiosis.

Additional concepts of industrial ecology that are useful in the island context are embedded utility, lifecycle perspective, resource cascading and tracking material flows (Chertow & Deschenes, 2003). These are described briefly here. Embedded utility refers to the total of all the energy and material used for extraction of materials, transportation, primary and secondary manufacturing and distribution of a product. To maximize embedded utility, cycling of goods and materials is emphasized in industrial ecology, which, in an island context, extends resource availability. A lifecycle perspective ensures a breadth of focus not limited to what happens within one facility or factory, but rather considers the entire set of environmental impacts that occurs at each stage of industrial development and use. The lifecycle perspective is important for identifying lifecycle phases for a product or a resource that have the greatest impact on the sustainability of the island system (Singh *et al.*, 2001).

The notion of cascading takes advantage of the idea of embedded energy (Sirkin & ten Houten, 1994). Cascading occurs when a resource is used repeatedly in different applications. In successive uses, the resource is of lower quality, a lower level of refinement or lower value. The benefits of cascading are numerous, including the reduced use of virgin resources, the avoided impact of resource extraction and reduced waste disposal. Material flow tracking is used to identify and quantify all significant material inputs and outputs of each firm in an industrial system (Bringezu & Moriguchi, 2002). The results are analyzed to suggest opportunities for exchange of materials among companies, as well as opportunities for more efficient resource use in the industrial ecosystem. The clear boundaries of an island context simplifies the tracking of flows (Andrews, 2001). Given the limited carrying capacity of islands, greater accountability through material tracking enables better control over inputs and outputs.

A Case Study: Puerto Rico

As a growing field, industrial ecology needs areas to study that are amenable to its approaches and can benefit from increased understanding of sustainable industrial development. Such areas must have the potential for industrial development as well as an evident need to incorporate sustainability considerations into their industrial systems. The island of Puerto Rico, with its diverse ecological and industrial systems discussed below, presents this type of setting for industrial ecological study. Examination of the industrial systems of Puerto Rico under the optic of industrial ecology was started by the Yale Center for Industrial Ecology in 2001. While research on site-specific projects in Puerto Rico is on going, the motivation to study an island such as Puerto Rico was established by the research team at the onset of the study based on the unique characteristics of the island context. Descriptions of Puerto Rico and a few of the specific studies underway are presented here to illustrate the potential utility of applying industrial ecology to the island context.

Study Site

Puerto Rico, one of the Greater Antilles, is a commonwealth of the USA located between the Caribbean Sea and the Atlantic Ocean. Its total land area is approximately 9000 km^2 (2 240 000 acres) with a population of approximately 3.9 million, giving the island a population density similar to that of the state of New Jersey, the highest in the USA. A true island, Puerto Rico has about 500 km of coastline and is home to the fourth largest container port in the world at San Juan. The natural geography of Puerto Rico ranges from coastal water systems to arid uplands and includes tropical rainforests among its diverse ecosystems.

The USA gained possession of Puerto Rico as a Commonwealth following the Spanish-American War in 1898. The first elected government of 1948 saw manufacturing as the path to development for Puerto Rico. The industrialization programme 'Operation Bootstrap' advocated: developing the local labour base; inviting investment of external capital; importing raw materials; and exporting finished products to the USA. This initiative included federal tax incentive programmes that exempted manufacturers locating in Puerto Rico from the majority of corporate income taxes.

Puerto Rico possesses few natural resources, mainly stone and marine fish as well as some copper and nickel. The primary industries in Puerto Rico, other than tourism, are high value added sectors that benefit from the tax incentives gained by locating on the island. In 2000 the pharmaceutical industry accounted for $20.8 billion in exports, 65 facilities, and over 25 000 employees. Sixteen of the top 20 prescription drugs in the USA are produced in Puerto Rico. The measuring, analyzing and controlling instruments industry (MACII) accounted for $1.8 billion in exports, 41 plants and 15 000 employees in 2000. The electronic and electrical equipment manufacturing industry accounted for $6.7 billion in exports, 85 plants and 17 500 employees in the same period. The plastics industry added another 76 plants and 4 700 employees (Puerto Rico Department of Economic Development, 2001a, 2001b; Puerto Rico Industrial Development Company, 2000). The industrial milieu of the islands also includes agriculture, food processing, power generation, textiles and petrochemicals. Puerto Rico has low labour unionization, and the national average wage is about two-thirds of that of the rest of the USA. About 53% of all 20 to 24 year olds are enrolled in higher education and 77% of the workforce are high school graduates (Puerto Rico Industrial Development Company, 2002). A highly educated and relatively inexpensive labour force, along with a host of tax incentives, have made Puerto Rico very attractive to foreign manufacturing firms.

Puerto Rico provides a unique and advantageous balance of accessibility and isolation for an industrial ecological study. Its political, economic and industrial systems are well documented in available databases and archives. Its close ties and proximity to the USA facilitate physical inspection and transparent analysis. As an island, Puerto Rico has well-defined boundaries across which established systems of accounting exist for materials flows. The island is large enough for a study of diverse industrial systems, yet small enough and isolated enough to engender the characteristics of the island context.

Sustainability Challenges

A brief survey of the resources of Puerto Rico indicates a number of sustainability challenges for the island. Primary among these is the need for sustainable energy options. Puerto Rico has none of its own fossil fuel resources, but 99% of the electricity generated on the island and nearly all of the island's energy come from fossil fuels (Energy Information Administration, 2002a). Puerto Rico must generate all of its own electricity. As a result, electricity costs for all sectors in Puerto Rico are much higher than in the continental USA.[6] Although Puerto Rico is a tropical island with high solar incidence and abundant wind resources on a number of coasts, neither of these renewable sources of energy have been developed commercially. Alternative transportation is virtually absent in the cities of Puerto Rico. Cars and some buses operating on gasoline and diesel fuel are the sole mode of vehicular transportation on the island.[7]

Puerto Rico relies on two principle sources of water. A large aquifer exists on the limestone bedrock in the northern portion of the island. Many industries, especially large pharmaceutical companies in this region, tap this resource via wells. Over-pumping and waste effluent contamination have begun to degrade the aquifer in places and concern has been expressed on the island over the functional lifetime of this resource. Salt water intrusion on the south of the island is another indicator of capacity limitations. Much of the island's water comes from collected runoff in reservoirs in the centre of the island. Reported water line losses as high as 40% are a concern for the sustainability of water supply (Puerto Rico Aqueduct and Sewer Authority, 1996). A large quantity of bottled drinking water is imported to the island,[8] but water is not imported for other uses.

The majority of material resources are imported to Puerto Rico, with a large portion of these imports coming from the USA. Puerto Rico mines some limestone and aggregate for use on the island, and approximately 480 000 hectares of its land are employed in agriculture (Estudios Technicos, 1997). About half of this is used for growing coffee and sugar cane for export. Mangoes, pineapples, melons and plantains are also grown for export. The remaining local agricultural production produces only a small fraction of the food consumed by the island's residents. The modest quantities of secondary material collected on the island are exported for recycling. Owens-Illinois operates a facility that manufactures glass bottles and is the only firm producing new products from secondary material on the island.[9] Puerto Rico is reliant on imports for most of its material resources with the exception of a few types of fruits and vegetables and few imported resources are effectively reused or recycled on the island.

Solid waste production on the island is very high, with estimates ranging from 8000 to 14 000 tons per day with less than a 5% recycling rate (Miranda & Hale, 1999; Mahoney, 2001; Rodriguez, 2002). The majority of solid waste produced in Puerto Rico is disposed of in landfills on the island. In 1993, there were 62 landfills, but by 1999 only 29 remained open as a result of mandatory closings (Autoridad de Desperdicios Solidos, 1999). Only four of these landfills are thought to be substantially compliant with environmental regulations, however leachate is not properly collected in any of the island's landfills causing significant fear of soil and groundwater contamination (Uemachi *et al.*, 2003). Given the lack of enforcement and compliance, it could be concluded that Puerto Rico has reached its assimilative capacity for municipal solid waste. Despite estimates that disposal capacity could last another 10 years, there is no plan to construct new landfills in Puerto Rico (Uemachi *et al.*, 2003). Only a few, experimental composting and land application projects are under way on the island. These focus on biosolids and cannery wastes. There are no waste incineration or waste to energy operations in Puerto Rico and this option has been largely precluded legislatively. Most hazardous waste is shipped off the island, although some pharmaceutical waste is incinerated on site by private operations.

Industrial Ecology Applied to Puerto Rico

Puerto Rico, during its short, intense industrialization over the last 50 years, has become a hub of manufacturing. Raw materials are imported and value added goods are exported, capitalizing on inexpensive skilled labour and a variety of tax incentives. Little effort is made to consider the limits of the island's natural environment when faced with global-scale production, throughput and consumption. Rapid industrialization in the island context has produced the numerous sustainability challenges listed above. As these challenges deal with flows of resources and the conflict between industry and natural carrying capacity, industrial ecology, which brings the tools of material flow analysis, cascading resource flows and life cycle accounting to the table, offers a unique problem solving perspective. At the same time, many of the limitations of the island context can be viewed as opportunities for sustainable development solutions based in industrial ecology.

In an effort to bring the concepts of industrial ecology to bear on the sustainability challenges of Puerto Rico, a number of studies have been carried out by the Yale Center for Industrial Ecology at specific sites on the island. A brief overview of three of these is presented here to demonstrate the potential utility of industrial ecology for addressing environmental sustainability on the island.

Pharmaceuticals. The size and concentration of the pharmaceutical industry in Puerto Rico make the firms in this sector a competitive cluster on the island (Ashton & Chertow, 2002). Fifteen pharmaceutical facilities are located around the municipality of Barceloneta in the northern part of the island. In the past, these companies have sought to work together on projects to address air emissions, water use, and waste production, but progress has been slow.

Fresh water supply and waste management are principal environmental concerns for these pharmaceutical manufacturing firms in Puerto Rico. A survey of the resource flows of the pharmaceutical companies shows a number of potential initiatives that could improve the existing operations, as well as the environmental sustainability of the participants. Some ideas from the Center for Industrial Ecology study that addressed water use included construction of a storm-water facility, common treatment in a dedicated wastewater plant, and extending agricultural and other businesses that use appropriately prepared water treatment sludge on hay crops and in teak forests. The study also showed the potential for:

- energy efficiency from a jointly operated co-generation power facility;
- transportation efficiency through a joint employee shuttle;
- secondary and tertiary packaging manufactured from secondary materials; and
- solvent recovery to be used by paint and cleaning compound manufacturers.

There is now evidence that the sustainability pressures predicted in the first part of this discussion are leading to the sorts of co-operative arrangements fostered by industrial ecology. As of 2003, eight facilities in the Barceloneta pharmaceutical cluster are joining together to address energy and water constraints simultaneously. Under a proposed agreement, the companies will supply wastewater to a new co-generation plant and will get back energy in the form of steam from the power station. While it could be argued that such organization is not limited to an island setting, co-operation at this scale is very unusual in North American facilities.

Manufacturing clusters. A number of industries are grouped together on the western side of Puerto Rico and make up the Puerto Rico Techno-Economic Corridor (PRTEC). This development includes groups of firms dedicated to information technologies, medical devices manufacturing and electronics manufacturing. A survey designed to quantify the collective material flows of 23 companies in PRTEC demonstrated the potential for new operations to recycle cardboard, metal alloys and isopropanol (Campos *et al.*, 2002). The volume of a material such as cardboard flowing from PRTEC may not be sufficient to drive a material recovery operation, but the proximity of all major sources of waste cardboard on the island to PRTEC could allow a recycled cardboard plant to be co-located. The size of the island limits transportation distances for the collection of secondary materials, and the ocean boundaries of the island can create an economy of local processing favoured over trans-shipment. The proximity of the companies and their service needs also suggest that efficiencies could be gained from siting collective catering, uniform cleaning and instrument sterilization services near the facilities. The efficiencies could be realized through reductions in the use of energy, water and materials, as well as through reduced transportation. These efficiencies have a greater value in the island context, where resources (water) are more limited and inputs (energy and materials) are more expensive.

Value added industries. A large trans-shipment port project called the Port of the Americas has been proposed for the southern part of the island. In conjunction with the Port project, there is a proposal for the development of a group of value added industries near the port. Already present on the chosen site are two power plants, an old oil refinery and a desalination facility. New development can incorporate the water, material and energy flows of these existing facilities to improve resource efficiency. An example is a beverage manufacturing operation, which uses excess desalinated water as a primary input, low-pressure steam from the power plants to provide refrigeration and cooling and packaging materials generated from reuse/recycling of materials from the surrounding value added industries.

The new port development can be implemented while minimizing environmental impact of new resource flows by increasing the cycling of existing resources. In the absence of the industrial ecology approach of tracking materials through their lifecycles and linking separate industries, the port would be just another large development project in the island context. The scale of material throughputs would provide economic development for Puerto Rico, while burdening the island with increased wastes and demand for energy and water. A view of the port development from the industrial ecology perspective offers options for increased energy and water use efficiency. Programmes to develop packaging reuse and recycling could make the port a sink for some secondary materials on the island, rather than a source of more waste for the strained waste management facilities of Puerto Rico.

These three examples alone will not solve the island-level sustainability challenges of Puerto Rico. The purpose of these studies is to demonstrate that by considering parts of the industrial system, their resource flows and the related impacts to the island environment, human activities can be planned to address the need for careful operation and development in the island context. The studies are themselves suggestions for developing sustainable industry within the broader context of Puerto Rico. Note that the examples presented include considerations of environmental sustainability as well as the potential for future economic development. Industrial ecology does not simply place industry within the constraints of the environment. Connectivity and complexity are promoted as a means to increase resource use efficiency while improving existing operations and creating opportunities for new businesses (Chertow & Deschenes, 2003).

The examples presented here show methods for improving Puerto Rico's overall environmental infrastructure: the efficiency of energy, water and material use and the reduction of waste through material cycling. Development solutions based on an industrial ecology perspective speak to the immediate sustainability concerns of Puerto Rico. At the same time, previous research suggests that the application of technologies to address environmental infrastructural needs are collective goods, the delivery of which is much more complex than the transfer of industrial technology to the supply of private commodities (Tisdell, 2000).

With this is mind; energy should eventually be produced in Puerto Rico primarily from locally available, renewable resources. While these resources are being developed, fossil fuel use can focus on new, cleaner technologies to provide cleaner energy for the island. If fossil fuel is combusted to produce electricity, methods of energy efficiency can reduce demand, and by-product steam can also be put to productive uses. An ethic of co-generation should prevail until renewable technologies can replace existing non-renewable generation.

In the short term, Puerto Rico cannot afford to use fresh water inefficiently. Proper wastewater treatment can help prevent the destruction of the island's aquifer and aquatic ecosystems as well as the fouling of fresh water resources. Collective partnering in major industries, such as pharmaceutical manufacturing, can motivate more efficient water use and increased waste water treatment, while lowering the overall cost of these activities.

It is unreasonable to expect Puerto Rico to forfeit all external inputs of material resources. However, imported materials are associated with a lack of resource security and the threat of waste generation beyond the island's assimilative capacity. Non-product materials can be used not once, but repeatedly. Local alternatives, such as recycled packaging and solvents, can be researched as substitutes for external inputs. Landfilling should be seen as an option that is severely limited by the size constraints of the island, and waste materials should be investigated for reuse and recycling or at least energy recovery.

An overview of the island's sustainability challenges and options provides an insight into the importance of industrial ecology in this island context at a summary level. The concentration of industrial activities embedded in an environment of limited natural resources and carrying capacity introduces immediate sustainability concerns, while creating facilitated conditions for numerous symbiotic interactions with the potential to mitigate and resolve these concerns. As research continues, more examples are uncovered that demonstrate the potential of symbiosis to address resource availability concerns in the island setting in industries such as rum production, food processing, cement and concrete and paper recovery (Yale CIE & FLMM, 2003).

Generalization of the Puerto Rico Case

The case of Puerto Rico suggests the question of generalization. If the argument holds that industrial ecology presents sustainability options of value to the island context of Puerto Rico, does it hold for others, and how can this approach benefit continental settings? Towle (1985) suggests environmental management solutions follow a hierarchy: small islands present a model for large islands, which present a model for continents. This simple model may not pertain to all applications of industrial ecology, but a generalization of the island approach is possible.

The approach to the Puerto Rico studies was to survey the industrial system of the entire island to identify smaller units of industry to facilitate research. This approach maintained the island context of Puerto Rico, while enabling the selection of interesting and manageable study units. A smaller island without the diversity of industry could not be studied in this way. For smaller islands, it may be appropriate to look at the whole island at once or an entire industrial sector on an island. Examples of this approach are available for the Swedish islands of Nambo, population 41, and Gotland, population 58 000 (Sundkvist *et al.*, 1999; Sundkvist *et al.*, 2001). In both cases, the authors use the context of a small island to isolate the need for sustainable development. The island context has also been used to develop a sustainable agricultural network at the Montfort Boys' Town in Suva, Fiji (Klee, 1999). It is reasonable to suggest that industrial ecology would find fertile ground on islands other than Puerto Rico, both small and large. The island of Singapore, for example, has to import most of its food and potable water, but has leveraged these constraints to become a world leader in the development of desalinization and advanced water purification and reuse techniques. As long as the island context holds and human industry is present, industrial ecology provides an insightful approach to sustainability challenges.

Heinz Wallner's theory of 'islands of sustainability' provides a theoretical link between the island approach to industrial ecology and a continental setting (Wallner *et al.*, 1996; Wallner, 1997). Wallner suggests that sustainability can be approached on a regional level by considering small clusters of industrial operations as islands, which he calls islands of sustainability (IOS). The individual IOS become nuclei of sustainability in a landscape of unsustainability. By then connecting these units of sustainability together, Wallner proposes the entire region can eventually be made sustainable. This final step requires less effort because the majority of human activity is already densely concentrated within the IOS. It may be possible to use this conceptual framework to approach a continental landscape as a collection of smaller island-like units, such as watersheds or bioregions. While some characteristics of the island context may not hold (isolation), others may endure this translation (scarcity of resources, such as water). As experience is gained with geophysical islands, the lessons learned should also be applicable to continental settings.

Conclusion

Engineers, environmental scientists and policy makers have developed and applied the principles of industrial ecology for well over a decade. In addition, material and energy flows have been studied for geographic regions in a number of settings (Boyden, 1979; Zucchetto & Jansson, 1985; Ayers & Simonis, 1994). The thread introduced in this discussion is the use of industrial ecology to examine sustainability challenges in the island context. As the case of Puerto Rico demonstrates, this approach is not just appropriate to islands; it is absolutely necessary. Societies across the globe will have to address the challenge of developing economic and technical evolution within the constraint of the carrying capacity of natural systems over the next century or so (Graedel & Allenby, 1995). Island societies will have to address this challenge much sooner, and industrial ecology focuses a powerful optic on the problem.

Islands benefit from the approach of industrial ecology, and the study of industrial ecology is benefited by islands. Islands face important sustainability challenges. There are few locally occurring natural resources and these are often in scarce supply. Resources are imported at the risk of supply interruptions and price fluctuations. Human development and industrial systems rely on ecosystem services from fragile and limited island ecosystems. The small size and isolation of islands force these challenges to the forefront of the planning horizon. Sustainability concerns in the island context are generally much more immediate than in the continental context. Industrial ecology, which considers industry embedded within the finite natural environment, presents a method for addressing these concerns in a way that considers environmental conservation as well as the necessity of economic development.

Conversely, industrial ecology studies benefit from the characteristics of the island context. The small and bounded scale of islands puts a manageable and definite boundary on the regional system, a luxury not often found in sustainability studies (Andrews, 1999). The characteristics of the island context increase the technical and economic feasibility of testing and implementing industrial ecology solutions. For example, Iceland has made a commitment to replace petroleum used by its fishing and auto fleets with hydrogen fuel cells in the next 30 years. The hydrogen is to be produced on the island from abundant natural geothermal and hydrologic energy resources. This industrial ecology approach to eliminating the sustainability concern of petroleum use established footing in an island context where it would otherwise meet much greater resistance at the continental scale, such as the USA. Lack of internal resources, import price volatility and willingness to pay for decreased carbon emissions improve the economics of the hydrogen strategy. The small scale and boundedness (cars cannot be driven off of the island) of the conversion improve its technical feasibility. Adaptation of this type is the approach used in industrial ecology for creating a sustainable society. This island context gives evidence that an industrial ecology approach is an important step on the pathway towards sustainability on islands in modern technological societies.

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Notes

1. Geographers accept Greenland as the largest island with 2.2 million km^2 of land area, while Australia is the smallest continent at about 7.6 million km^2. Human population does little to shed light on this distinction as Taiwan, population 22 million, land area 36 000 km^2, is definitely an island although it is more populated than many continental states. The population of Australia is about 19 million, while that of Greenland is a mere 21 000.
2. Openness has also resulted in the phenomenon of 'brain drain', whereby the most well-trained human resources leave an island to pursue greater opportunities elsewhere (McElroy & de Albuquerque, 1990).
3. The Alliance of Small Island States (AOSIS), formed at the Second World Climate Conference in 1990, and Small Island Developing States (SIDS), formed at the United Nations Conference on the Environment and Development in 1992, are examples of diplomatic efforts to gain recognition for concerns over the impact of global climate change on islands. Sea level rise is not the only impact of concern. While some studies show that large, continental nations, which have a diversity of climates, may realize some positive effects under certain climate change scenarios

(Mendelsohn *et al.*, 1994), islands often have a single climatic zone that would be negatively affected.

4. Industrial ecology encompasses a broad range of concepts and analytical tools. A subset of these deals with industry on a geographical level. For this discussion of island systems, industrial ecology will be used to refer to this subset. For a more complete taxonomy see (Boons & Baas, 1997).
5. The waste exchanges alone amount to some 2.9 million tons of material per year (Lowe *et al.*, 1995). Water consumption has been reduced by a collective 25% and 5000 homes received district heat (Industrial Symbiosis Institute, 1995).
6. On average, industry in Puerto Rico pays $0.10/kWh for electricity, well in excess of the USA average of $0.068/kWh paid by all sectors for electric power and only $0.045/kWh paid by the industrial sector in 2000 (Stewart, 2002; Energy Information Administration, 2002b). Puerto Rico's utility monopoly and social policy contribute to the high cost of electricity for industry on the island.
7. A light rail system called Tren Urbano has been under construction in San Juan for over five years. It is currently faced with cost overruns and does not have a set date for the beginning of operation.
8. 7.6 million litres in 2000 (Puerto Rico Planning Board, 2000).
9. At the time of this writing, it was not determined what portion of the secondary glass cullet used at Owens-Illinois was recovered from Puerto Rico's waste stream and what portion was imported from the USA.

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