Energy Implications of Materials Processing

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Energy, the capacity to do work, comes from a variety of fuels. Much of the work that society requires is the conversion of materials to a useful state. Without the energy from coal, oil, natural gas, nuclear power, and other sources, very few materials could be produced on the scale we are accustomed to. Thus, the broad-based, consumer-oriented industrial society that we now enjoy would be impossible.

During the 20 years from 1950 to 1970 the real cost of energy declined significantly; energy commanded $0.25 per million British thermal units (Btu's) (*1*) in the marketplace, and vast segments of society considered it as available as water from the tap. Increasing affluence, expectations, and population levels created tremendous demands for the cheapest, cleanest, and most convenient forms of energy; increases in fuel costs for environmental protection were discounted. Few believed warnings such as Hubbert's (*2*) that we would soon need to end such profligate consumption patterns.

Cook (*3*) estimates that human labor, at $3 per hour, costs $6000 per million Btu's; since human labor is the most expensive energy, industrialization can be defined as substituting fuel energy for human energy. Today society does not face the problem of running out of energy as much as it faces the task of changing its entire pattern of fuel consumption. This task is as difficult as any encountered since the industrial revolution began. Chemical engineers have traditionally performed materials and energy balances in their research. Such balances are needed today, as never before, because our accounting for energy consumption must go far beyond knowing that the steel industry consumes 5 percent of the nation's total energy supply or that to produce 1 pound of aluminum requires 6 to 8 kilowatt-hours of electricity in the smelting step. Today energy accounting, particularly in the materials world, must be precise and sophisticated.

Energy accounting, in the materials world, is an increasingly complex problem. The term materials is defined by Webster's as "the substance or substances from which things are or may be constructed." That definition, implying structural materials, has been broadened to include both fibers and fuel minerals; only food is still excluded. Thus, energy accounting must include metallic and industrial minerals, plastics, chemicals, and fuel minerals. The efforts of industry to extract these materials from nature and convert them to useful states requires more than one-fifth of the total U.S. energy budget.

← *Courtesy Stuart Finley, Falls Church, Virginia*

General Approach

The definition of materials used in this article includes fuels as well as structural materials. Thus, in the analysis of amounts of energy required to produce usable substances, energy, materials, and dollars are exchangeable. Rigorous analyses of materials processing systems to determine unit energy requirements were not done systematically until the last few years. Such evaluations of metals, chemicals, and other commodities are just now coming into the scientific literature (*4–8*).

Each material requires its own analysis development under some broad guidelines. In one methodology, any specific materials analysis covering a commodity must be large enough to include the entire industry of any nation. All degrees of technological progress must be represented in the final output figures. Modern facilities must be taken together with outmoded plants and their energy efficiencies averaged. For example, zinc recovery systems vary in efficiency from 60 to 85 percent; all operating levels must be included.

Both upper and lower bounds limit energy analysis. The studies are constrained by the total gross energy figures of the United States. In the last 4 years this country consumed 69 to 73 quads (1 quad = 10^{15} Btu's) annually. The total energy used cannot exceed this figure. Data from the Bureau of Census (*9*) and the Bureau of Mines (*10*) provide more refined summaries of the total energy expended by specific industries; these values are upper limits for the particular industries. Lower limits include, for example, the energy used in the construction of a grinding mill or the calorific value of human labor. Such data are insignificant in overall energy studies dealing with tens of millions of Btu's per ton of material. The whole subject of energy subsidies in the form of research, processing plants, and true net energy are covered in the paper by Gilliland (*11*).

Society must know the energy requirements of all industrial materials for many purposes. The most important are for determining (i) the energy intensiveness of specific materials, (ii) the national requirements for specific materials industries, and (iii) energy flow diagrams paralleling process flow diagrams. These factors help guide the selection of materials. Further, they aid those seeking to conserve energy in present systems and to minimize energy requirements in developing new technologies.

Metallic Materials

Several studies have appeared in the last 3 years: most recently, the Battelle Columbus Laboratories performed a complete evaluation of energy in materials for the Bureau of Mines (*12*). Battelle employed basic metallurgical flow sheets, starting with ore in the ground and proceeding through the steps of mining, transportation, concentration, and reduction to the metallic ingot stage. They then assigned energy consumption rates to each step in the flow sheets. Census data, Bureau of Mines surveys of industrial consumption and production of energy, information on industrial operating experience from several sources, and other published information provided the basic energy data. In the Battelle study all energy inputs were converted to a common factor, British thermal units; a value of 10,500 Btu's (thermal) per kilowatt-hour was used for electricity.

Two metals, copper and iron, are of particular interest because of their significance to society. Copper is important because it is such a good conductor of electricity and heat; these properties are essential in an industrialized society. Iron and its alloys are the most versatile metallic materials available to man and are produced in the largest amounts. Without copper and iron the U.S. economy could not hope to meet the demands of the people.

A simplified flow sheet for processing 1 ton of copper from a sulfide ore containing 0.7 percent copper (near the current average grade) appears below. The energy con-

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sumed in each step, expressed in millions of Btu's, appears in parentheses. The accuracy of the total energy was estimated to be ± 10 percent (*12*).

Mining (21.6)
↓
Concentration (42.3)
↓
Smelting (38.2)
↓
Refining (10.2)
↓
Refined copper (112.3)

Some copper is recovered by leaching heaps and waste dumps with sulfuric acid. The process precipitates the copper from solution, electrochemically, with ferrous scrap. A separate flow sheet developed for that segment of the industry shows the energy (10^6 Btu's) needed to produce 1 ton of cement copper.

Sulfuric acid solution
(largely self-generated)
↓
Pumps (41)
↓
Waste dumps (0)
↓
Precipitation (45)
(2½ tons detinned steel cans)
↓
Cement copper (86)

Copper requires between 86 and 112 million Btu/ton. This high energy consumption stems from problems associated with the relatively low grade of the ore. Iron and steel require far less energy per ton of material produced.

The flow sheets developed for the production of steel slabs appear as follows, beginning with the traditional open-hearth furnace approach.

Blast furnace (17.4)
↓
Open-hearth furnace (6.1)
↓
Ingot casting (0.74)
↓
Slabbing mill (1.9)
Total: 26.1×10^6 Btu/ton

The basic oxygen furnace consumes slightly more energy because less scrap (and more hot pig iron) is used. The energy flow sheet shows 21.8×10^6 Btu/ton for the blast furnace and 2.8×10^6 Btu/ton for the basic oxygen refining operation, giving a total of 27.2×10^6 Btu/ton.

The third steel process, the electric furnace, uses a 100 percent scrap feed. The energy flow sheet appears as follows.

Scrap (0)
↓
Electric arc furnace (10.0)
↓
Ingot casting (0.74)
↓
Slabbing mill (1.9)

for a total of 12.6×10^6 Btu/ton. This low figure for steel from scrap represents a subsidy from the original blast furnace reduction. Note that in this case the iron is available for further recycling, whereas in cement copper the iron was consumed and therefore an energy charge. It is also a graphic demonstration of the importance of recycling.

The energy used by ten metal industries is summarized in Table 1. These ten metals accounted for 5.45 quads of the estimated total of 5.8 quads used by the primary metals industry in 1973, or almost 8 percent of the country's total energy consumption. A minor amount of energy was imported in the form of bauxite, iron pellets, chromite, and other raw materials. For purposes of uniformity, however, the study assumed that all materials processing occurs in the United States. Energy imports are offset by energy exports in the form of finished products.

An important factor to be considered is the energy expenditures associated with using plentiful domestic resources of lower-grade ores. Bravard *et al.* (*13*) calculated the added energy rquired for producing five metals from lower-grade ores. In the case of aluminum, lower-grade bauxite or clays would be favored over anorthosite for long-term development, the processing costs being nearly equal. The problems associated with processing lower-grade ores are due to the increased volume of material, which requires higher energy inputs for mining and transportation and a greater percentage of the total energy to be used in crushing and grinding. Kellogg (*14*) concluded that the most important element is the grade of ore. This is demonstrated in Table 2, taken from unit studies of the Battelle report.

The results given in Table 2 can only be considered indicative. For instance, 36 percent of uranium is mined underground, and the mining energy for that portion would be several times higher than the energy for surface mining. A straight-line projection of the figures for producing 1 ton of copper shows that for ore containing 0.18 percent copper, 628 tons of ore would have to be processed, 1840 tons of waste would have to be moved, and the energy for mining and concentrating would constitute 84 percent of the total process energy.

This is the same general trend shown by Kellogg (*14*) and Chapman (*5*) and is indicative of the rising energy costs of mining lower-grade nonferrous ores. It is only increased use of energy through mechanization that has made mining of such ores possible. Lovering (*15*) estimated that while U.S. mineral production rose 50 percent in the last 50 years, energy consumption went up 600 percent in the last 25 years.

There are three ways to counter this: (i) using better technology, such as a cheaper grinding process or in situ leaching; (ii) recycling, which uses 5 to 30 percent of the energy required to produce metals from ores; and (iii) making better use of the metals we produce—for example, doubling the life of an automobile.

Nonmetallic Materials

The nonmetallic sector consumed 1.9 percent of the total U.S. energy in 1973, and half of this was in portland cement production alone. Some of the largest users in this class are shown in Table 3.

As a class, nonmetallics are almost an order of magnitude lower in energy intensiveness per ton than metallic materials. This is because they are much more common in nature, and they are generally processed "as is" without reduction of oxides or silicates or breaking of chemical bonds. However, they are highly transportation sensitive. Truck transportation of sand and gravel, for an average of 20 miles, uses more energy nationally than the magnesium industry. Thus, materials can be energy intensive like titanium, with a high energy requirement per ton, or they can be low like cement, but the national aggregate is substantial.

Energy Costs of Fuels and Electricity

A national energy accountability system also requires knowledge about energy inputs to such industries as coal mining, petroleum refining, and natural gas transmission. Adding their processing costs to the thermal value of the fuels produces total energy costs. In its own right, the extraction, conversion, and transportation of energy is the most energy-consuming sector of the American industrial scene. More than 20 percent of the gross energy of fuels is consumed in bringing energy to the materials processor. In practice, as described in this article, it is necessary to start with gross energy in arriving at energy costs per unit of material and, in effect, assign all these energy losses to specific materials. The energy unit costs of petroleum, natural gas, coal, and electricity will only be covered in general terms.

Coal production involves relatively low extraction and transportation losses. Capital, materials, and equipment, estimated at 2 percent of the fuel value, would represent 500,000 Btu/ton. The Bureau of Mines estimates that in 1973 it required $31{,}300 \times 10^6$ Btu's to mine and prepare a ton of coal for market. It is estimated that the transportation energy is 330,000 Btu/ton for a total of 861,000 Btu/ton delivered coal.

Petroleum is not such a simple case. Capital and equipment costs probably represent 2 percent of the fuel value. Lease and plant fuel value would add another 2 percent. Transportation by pipeline and tanker to a refinery also represents about 2 percent of the crude energy value. The refining operation itself uses tremendous amounts of petroleum fuels, natural gas, and electricity, which translate to more than 700,000 Btu's per barrel of crude oil. This amounts to 11 percent of the total energy to refineries, counting both crude oil and auxiliary fuels. On a national scale, it amounted to 2.83 quads in 1968 or 4.7 percent of the total energy of the United States. The petroleum industry consumes about 17 percent of its own energy equivalent in going from exploration to distribution of refined products.

In the United States 3 percent of all natural gas is used as transportation fuel for pumping the gas from well to consumer. Lease and plant fuel used in extraction probably account for 2 percent. Other energy costs represented by equipment and capital are also estimated at 2 percent, so that 93 percent of the fuel value is delivered.

The energy costs of bringing fossil fuels to market are shown in Table 4. In energy accountability this shrinkage is assigned to specific classifications such as extraction, petroleum refining, and transportation.

Electricity, a secondary energy form, is far and away the most expensive [as well as concentrated (*11*)] in terms of energy cost. Yet, it is the fastest-growing sector. Some two-thirds of the input energy of the fossil (as well as nuclear) fuel is dissipated either in its transmission to the user or up the smokestack and down the river in the cooling water. In 1971 the United States consumed 25 percent of its gross fuel inputs to produce electricity. It used a gross of 17.4 quads and lost the greater part of 11.9 quads in the production and transmission processes. Some small fraction of the waste heat was used. In discussions of energy per unit of output, the conversion of electrical energy has to take this loss into account. Theoretically, the conversion of 1 kilowatt-hour of electricity provides 3413 Btu's, but more than three times that much thermal energy is needed to generate and transmit that much electricity. A figure of 10,400 Btu's (thermal) based on actual industry measurement is generally used in this country. This figure has come down from a heat rate of 15,600 Btu's per kilowatt-hour in 1947.

In summary, the energy inputs of fuels for materials processing in the United States in 1971 were 12.56 quads for coal, 30.49 for petroleum, 22.73 for natural gas, 2.80 for hydroelectric power, and 0.41 for nuclear power—a total of 69 quads. Prorating electricity conversion losses and subtracting 5.7 percent for nonfuel uses (feedstocks, lubricating oils, and road materials) gives a net energy output of 57 quads.

Energy Costs of Plastics and Chemicals

More than 90 percent of the feedstock of fuel and petroleum products in the United States is used in a half-dozen chemical industries (*6*). Gross energy inputs can be measured, as well as energy contained in the primary products. Past this point, the distribution or determination of energy per unit of material becomes stickier. For in-

Table 1. Energy requirements for selected metals in the United States in 1973 (*12*).

Commodity	Product	Energy required: Per net ton product (10^6 Btu's)	Energy required: Total (10^{12} Btu's)
Iron and steel	Steel slabs	24	3350
	Gray iron castings	34	366
	Carbon steel castings	42	54
Aluminum	Ingot	244	1170*
Zinc	Ingot	65	92
Lead	Ingot	27	23.9
Copper	Cement copper	87	14.9
	Refined copper	112	221
Chromium	High-carbon ferroalloy	61	15.8
	Low-carbon ferroalloy	129	19.5
Magnesium	Metal	358	42.0
Manganese	Ferromanganese	49.5	33.0
	Blast furnace	46	17
	Electric furnace	52	16
Titanium	Metal	408	8.2
Uranium	Uranium oxide		
	Acid circuit	776	2.1
	Alkaline circuit	1123	2.2
	Resin-in-pulp	795	2.3

*In practice, 40 percent of aluminum electrical energy in the United States is derived from hydroelectric plants. The figure 244×10^6 Btu/ton in the Battelle report is reduced to 204×10^6 Btu/ton in calculating total U.S. use of 1.17 quads.

Table 2. Energy expenditures in mining and concentrating selected metallic ores.

Commodity	Grade (%)	Tons ore per ton metal	Energy per ton product (10^6 Btu's): Mining	Energy per ton product (10^6 Btu's): Concentration	Percentage of total product energy
Iron	30	4	0.61*	2.0	11†
Zinc	10‡	12	5.3	5.2	7
Lead	10‡	12	4.3	4.5	30
Copper	0.7	157	21.6*†	42.3	57
Uranium	0.2	530	332.4*	246.6	58

*Surface mining. †Pellets. ‡Estimated.

Table 3. Energy requirements for selected nonmetallic materials for primary products in the United States in 1973.

Commodity	Product	Energy required: Per net ton product (10^6 Btu's)	Energy required: Total (10^{12} Btu's)
Calcium	Quicklime	8.5	182
Cement	Portland cement	7.6	688
Ceramics	Common brick	3.5	62
Glass	Glass containers	17.4	216
Refractories	Basic brick	27	18.2
	Fireclay brick	4.2	6.9
Clays	Kaolin	2.8	14.3
Gypsum	Other clays	0.1–5.3	16.7
	Calcined gypsum	1.5	19
Sand and gravel	Sand and gravel	0.056	53
			1276.1

stance, ethylene accounts for not only its own feedstock requirements, but also those of ethylene oxide, ethylene glycol, and, in part, ethylbenzene and styrene. Also, ethylene produced from naphtha contains propylene, butadiene, benzene, toluene, fuel gas, and other by-products. It is beyond the scope of this article to trace out allocations of energy below the primary processing step.

The industrial use of energy for 37 selected chemicals in six standard industrial classifications (SIC's) in 1973 is shown in Table 5. The total represents 4.8 percent of all U.S. energy in that year. The six largest energy consumers in this group are shown in Table 6. Ethylene represents stored energy in that the creation of the double bond requires extra process energy. This energy can be released in later manufacturing operations involving ethylene dichloride or polyethylene. The triple bond in acetylene is also reflected in its high unit value.

The phenomenal growth of the plastics industry merits special attention (*16*). The process energy requirements range from 45×10^6 to 70×10^6 Btu/ton for polystyrene to 135×10^6 Btu/ton for low-density polyethylene. The plastics produced in the United States in 1973, estimated at 14×10^6 tons, required 1.4 quads of process energy, making plastics a larger consumer than the aluminum industry. The stored energy in the finished plastic is roughly equivalent to the hydrocarbon input and requires a raw material input of 0.6 to 0.8 quad. The only way to recover this energy is by combustion. This demonstrates that the plastics industry is one of the largest users of materials processing energy. However, unlike scrap metal, the material discarded by consumers can only be recycled as a fuel because of the present limitations of resource recovery technology.

Implications

Processing of many materials could become energy-limited rather than resource-limited. The methods required to provide metals, industrial minerals, and energy fuels and materials in useful forms all consume significant quantities of coal, oil, gas, and electricity. The materials industries use more than 20 percent of the nation's energy in processing metals (8 percent), chemicals and allied products (7.8 percent), petroleum refining (4 percent), and nonmetallics (2 percent). Steel, aluminum, plastics, cement, and gasoline account for half of this. The issue becomes complex when one considers that each material has its own level of energy intensiveness and that there are many ways in which energy can be lost or saved in the total economic system. Despite those problems, certain broad implications emerge for metallic, nonmetallic, and energy materials.

The data available for metallic minerals are the best defined. Further, the significance of metallics in the economy carries a clear requirement that energy intensity be considered in planning for their extraction and usage. Within that context, it becomes tempting to oversimplify the problem. For example, some 25×10^6 Btu's are needed to produce a ton of steel and 245×10^6 Btu's to produce a ton of aluminum. Thus, energy accounting might appear to mandate use of steel in preference to aluminum. But a ton of steel occupies one-third the volume of a ton of aluminum, so that substituting aluminum would greatly lower the energy savings per volume of material used. Further, for goods that are transported or used in transportation, lighter-weight materials provide additional energy savings. The same reasoning applies to plastics. Thus, energy accounting cannot provide as simple an answer as might be assumed from the initial data.

Table 4. Energy costs of bringing fossil fuels to market.

Commodity	Energy used	
	Percent	Btu's per 10^6 Btu's
Coal	3	30,000
Petroleum	6	60,000
Petroleum refining	11	110,000
Natural gas	7	70,000

Table 5. Energy requirements of six SIC groups in 1973. Numbers in parentheses identify SIC groups.

Industry	Energy (10^{12} Btu's)		
	Process	Feedstock	Total
Alkalies and chlorine (2812)	475.8	0	475.8
Industrial gases (2813)	110.5	48.9	159.4
Inorganic pigments (2816)	35.1	0	35.1
Industrial inorganics (2819)	442.5	345.6	788.1
Cyclic intermediates (2815)	70.1	158.7	228.8
Industrial organics (2818)	556.9	1273.5	1830.4
Total (281)	1690.9	1826.7	3517.6

Table 6. Six largest users of energy in SIC group 281 in 1973. Only feedstocks not accounted for by one of the other selected chemicals are included. For example, benzene is charged against styrene while ethylene is not.

Chemical	Tonnage (10^9 pounds)	Energy consumption (10^{12} Btu's)		
		Process	Feedstock	Total
Ethylene (2818)	33.4	382.3	1078.0	1460.3
Ammonia (2819)	30.3	271.7	345.6	617.3
Chlorine (2812)	19.2	398.6	0	398.6
Styrene (2815)	6.0	51.1	86.6	137.7
Methanol (2818)	7.04	34.3	91.7	126.0
Acetylene (2813)	0.58	8.27	38.8	47.1

One clear planning precept does emerge, however. Each material has a fixed lower bound of ore grade, below which energy costs make processing uneconomic. As noted above in the case of copper, the energy costs rise rapidly as ore grade decreases. At some lower limit, say 0.25 percent, the energy expenditures dominate the whole recovery picture. Technological improvements in rock disintegration, transportation, and concentration will have to be made if such low-grade ores are to be considered reserves—that is, resources that can be processed economically.

In the case of energy materials, both extraction and refining have serious energy implications for the economy. As extraction becomes more difficult and more refining takes place, more energy is lost. For example, two-thirds as much oil as has ever been found is still in the pores of the host rock. One of nature's contributions to oil extraction has been the pressure of the accompanying natural gas, which forces petroleum through pores to collection centers of drilled wells. Most secondary methods of recovery involve pumping of various chemicals and fluids to force out the oil. The pumping energy alone places finite limits on the amount of total petroleum eventually recovered from different reservoirs. Also, more energy is used today in the search for oil—40 years ago 275 barrels of oil were found per foot of hole drilled; the comparable figure today is on the order of 25 barrels.

The refining of petroleum presents one example of energy losses incurred in making a fuel more useful. Conversion of solid coal into more useful products by gasification or liquefaction presents another example. About 10 to 20 percent of coal energy is expended in making a low-Btu gas (170 Btu's per cubic foot) and another 15 to 25 percent is used in upgrading it to pipeline-quality gas (1000 Btu's per cubic foot). Electricity, the most ubiquitous and concentrated energy form, offers the ultimate example of energy losses incurred in a refining process.

The interweaving of energy losses in metallic and energy mineral processing can be dealt with, but only through a total systems analysis. Chapman (*5*) cited data on smelting copper by thermal-fired compared to electrical-heating sources. At first glance, electricity is favored 2 to 1 on the basis of heat input, but when heat rate is factored in the ratio is almost 2 to 1 against electricity. The moral of this example is best expressed in Chapman's words: "It is a disturbing conclusion that in good faith an industry could improve its own thermal efficiency whilst increasing the national energy consumption."

It is that total systems analysis, of true energy costs and possible real energy savings, which is required if industry is to meet society's demand for materials in a world where energy, in all forms, is becoming increasingly expensive.

References and Notes

1. Some conversion factors for units used in this article are: 1 Btu = 1.3×10^3 joules; 1 pound = 0.37 kg; 1 mile = 1.6 km; 1 cubic foot = 0.028 m^3.
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Tensions Between Materials and Environmental Quality

Environmental regulations will constrain the availability and increase the cost of materials.

Richard A. Carpenter

Concerns about environmental quality interact in a complex way, depending on supply and demand of materials, to change usage patterns, availability, and costs. The energy and materials conversion systems of industrial society are closely linked to natural systems of photosynthesis and biogeochemical cycles. The National Commission on Materials Policy (*1*, p. 6-1) concluded that:

> The material resources and environmental quality of the Nation are affected by a lack of consideration of the two as a unit. Depletion of reserves and pollution have the same cause—failure to manage the flow of materials as a cycle, resulting in a resource depleting dispersal of energy and materials into the environment as pollutants. A national policy for the management of energy and materials is needed to transform this open-ended process of wastage into a substantially closed system.

This relation is well recognized but very difficult to deal with. Thus, considerations of major parts of the whole, such as this special issue on materials, are practical devices for analysis and planning only as long as the total context is not forgotten.

Environmental quality is a relatively recent gathering point for a variety of measures—both quantifiable and subjective—of importance to the management of natural resources. The National Environmental Policy Act of 1969 sought to place the full fair weight of environmental values on the scales of the decision-making process. The Congress declared a national policy "to create and maintain conditions under which man and nature can exist in productive harmony . . ." (*2*). The National Materials Policy Act of 1970 sought to "enhance environmental quality" and develop a policy "to anticipate the future materials requirements of the Nation and the world . . ." (*3*).

The mixture of objectives within and between these two recent legislative expressions of national policy shows the development of thought about natural resources management. Neither exploitation nor preservation is dominant as a concept; a continually refined balancing among many goals is what is called for. Rather than making simple decisions whether or not to proceed with individual projects, the manager of natural resources is challenged to generate imaginative alternatives taken from as comprehensive a view as is reasonable. Trade-offs are to be made explicitly and in a process open to the public. The marketplace, with its time limitations and imperfect information about environmental impacts, has been augmented (or perhaps supplanted) by a growing array of assessment procedures and regulations. In fact, the single greatest source of tension between availability of materials and environmental quality may well be the increased difficulty and time lag involved in reaching acceptable decisions.

The desirability of balancing competing and often conflicting objectives in the use of natural resources leads directly to a second major problem: the dearth of complete, accurate, and timely information. Cause and effect relationships in ecosystems are not well understood because of the complexity of organisms and their environments. Ecology is not a predictive sci-

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