Ecocomposites: from the sustainable past to a sustainable future

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Abstract

We are moving from the Age Of Alloys, Plastics and Pollution to Age of Composites, Non-Renewable Resources Waste and Pollution; but if we are wise we can make a transition to the Age of Ecocomposites with virtually no pollution. Ecocomposite materials are those made with natural fibers and resins and can be produced in sustainable agro-industrial ecosystems. These materials can reused, recycled or returned to nature by grinding, composting, biological breakdown, or benign solvents. Historical use and recent rediscovery of these materials has suggested the many advantages (and challenges) using these materials offer to designers and engineers. By mimicking nature we can develop ecological farming and farming systems and an industrial ecology that is clean and safe and produces durable and high performance materials and improve the sustainability of our Society.

Author Keywords: ecocomposite, biocomposite, green composites, bioplastics, biopolymer, natural plastics, natural fibers, industrial ecology, biomimicry

1. The problem is

The birch bark canoe is made entirely from materials found in the forest: birch bark, cedar, spruce roots, ash and pine gum. When it is damaged it can be repaired easily from the materials at hand. When it has served its purpose it returns to the land, part of a never ending cycle. Once you begin to understand this cycle of growth, manufacture, use and return to the land you begin to understand why our modern culture is in such trouble. The non-cycle of growth, manufacture use and garbage is a dead end. Bill Mason, 1999.

The rapid economic growth and globalization of industry has come at a very high cost. Even in developed countries the rules, regulation and incentives for environmental protection have proved unable to check the harmful effects on human health and managed and natural ecosystems. Most pollution control efforts until recently have been focused on factory emissions, and favored end of pipe solutions rather than process change (Andersen, 1994; Elkington, 1997; McDonough and Braungart, 2002). It is clear that bolder initiatives are needed, particularly in choices of materials and chemicals for the reduction of pollution and damage throughout the product life cycle (Hundal, 2002; Scheer and Rubik, 2006; Wolters, 2003).

Material choices today are typically predicated on a straightforward analysis of lowest first cost for the required weight and strength. The cost is narrowly defined and ignores the environmental costs of pollution, and non-renewable resource consumption associated with mining, processing, manufacturing, maintenance and disposal. It also ignores the many health risks and social associated with use and disposal of the product (Papanek, 1985; Antheaume, 2004; Bainbridge, 2006). The problem is compounded by poor internal accounting for costs, with polluting products in a company often being subsidized by clean products (Schaltegger and Müller, 1998). If true costs were known many current market transactions would not occur, and we would face a much more hopeful, secure and sustainable future (Robért et al., 2002; McDonough and Braungart, 2002). Incorporating true costs in the market is probably the most important thing we can do, letting consumers choose the sustainable option because it is the best investment (Young 2006).

More than 100,000 chemicals are in use, but only a few have been studied in sufficient detail to predict environmental and health effects ( ). The complex range of possible interactions and breakdown products remain virtually unstudied. We don't even know where they go, let alone what they do. A key step is developing accurate materials accounting or balancing data so that we know where things go. To understand the full costs of both human and ecosystem effects we need to know much more about material flow (Brigenzu et al., 2000; Pedersen and de Haan, 2006). This is something chemical engineers have studied for decades within facilities and companies, but all too often the boundary has been the edge of the plant – not the atmosphere, stream, field or organism where small amounts end up and wreak havoc (Reck et al., 2006; Driscoll et al., 2007). Even seemingly innocuous materials that are currently poorly regulated or studied can be ecotoxic. These include nitrogen and phosphorus, which can be very hard to manage, but can have devastating effects on both terrestrial and aquatic ecosystems (Bainbridge, 1997; Vitousek et al., 1997; Günther, 1997).

Developing industrial systems that mimic natural ecosystems, are fully recycling with closed resource loops and no wastes, based on renewable energy, and using safe materials and processes is the tremendous challenge now facing industry and engineers around the world (Graedel and Allenby, 1995; McDonough and Braungart, 2002). One of the important elements in this revolution will be the use of ecocomposite materials.

2. Ecocomposites

Human history is often identified by the materials and technology that reflect human capability and understanding at the time. Many time scales begin with the Stone Age, which led to the Bronze, Iron, Steel, and Plastic Ages as innovations and improvements in refining, smelting, manufacturing and material science made new products available at reasonable "prices," but often with very high environmental costs (for a discussion of more complete ecological accounting see Bainbridge, 2006). In the 1980's the Age of Composites began to emerge, represented at its extremes by the Stealth bomber, Formula 1 racecars, racing boats, and the Solar Challenger. New advances in composite materials continue to reshape the world, but many of these have used toxic materials and little effort has been expended to make these “clean and green” composites. We might in fact say that we have moved from the Age of Alloys, Plastics, Waste and Pollution to the Age of Composites, Plastics, Waste and Pollution. If we are wise we can make a transition to the Age of Ecocomposites based on renewable resources with virtually no pollution or risk to human health.

Ecocomposite materials are made with natural fibers and bio-based matrix materials, where the fibers remain identifiable in the matrix material (Bainbridge, 2001, 2006). These can be produced in natural or industrial ecosystems, and recycled by regrinding, composting, biological breakdown, or benign solvents. Historical use and recent rediscovery of these materials has suggested the many advantages (and challenges) these materials offer to designers, engineers and manufacturers. By mimicking nature we can develop ecological farming systems and industrial ecologies that are clean and safe and produce durable and high performance materials that contribute to the sustainability of our society and our species.

Innovative developments and market forces now herald the beginning of the Ecocomposite Age using natural fibers and natural or synthetic matrix materials for a wide range of applications (Bainbridge, 2001). Ecocomposites can be more environmentally friendly and less hazardous to human health than synthetic materials produced from non-renewable resources, often perform as well or better, and can be disposed of by composting (Herrmann et al., 1998; Lang, 2002; Bainbridge, 2003). But just because it is natural doesn’t mean that it will be safe, careful research on ecosystem and health effects will be needed to select safe natural materials.

Note: Although the term biocomposites has been used to denote natural material composites, it is increasingly used for biological materials used in medicine, so the term ecocomposites is recommended and used here, after (Bainbridge and Lwin, 2001).

2. Lessons from nature

Over the long course of human history we have relied primarily on natural and ecocomposite materials to meet our needs. These materials were easily gathered, processed with simple and generally non-hazardous and non-polluting treatments, and when discarded simply melted away under the influence of weather and biological decomposition We can learn a great deal by more carefully analyzing our ancestors choices, based on their extensive experimentation and experience over thousand of years. We may no longer need to use sinew backed bows, fabricated using wood, fish bladder glue, and sinew fibers, to put food on the table; and we may not want a thin walled *kotni* (granary) of India, built with a mix of clay, cow dung and husks in our kitchen; but we may well reconsider wall systems made with straw and earth and a wide range of building products, structures, furniture and products made with ecocomposites (Steen et al., 1994; Lorenz, 1995; Mendler, 1996; Bainbridge, 2001; King, 2006). We may soon be driving cars built with natural fiber and resin composites that run on biologically derived fuels and lubricants (Anon, 1998; Faulkner et al., 1999; Summer, 2002).

Learning design and manufacturing lessons from nature is particularly important. Long before human history began the processes of evolution, testing, failure and redesign led to very sophisticated design and manufacturing processes in Nature. We can learn a great deal by studying the natural ecocomposites that have developed. Plant cell walls and plant structures are usually composite materials with regular arrangement of reinforcing materials (Niklas, 1992). Evolution over millions of years has led to complex structural design in many organisms (Pearce, 1978). Wood for example, is perhaps best described as a fiber reinforced structural foam. It has proved critical for our species, for tools, shelter, boats, bridges, airplanes, weapons and furniture. Even today wood is extensively used and recognized as a valuable structural material. Many other plant components also provide excellent raw materials for fabricating materials, structures, tools, and equipment (Herrmann et al., 1998; Bainbridge, 2001; Head, 2001). Natural fibers and plant structures and natural resins, plastics and foams can be used to make high strength but light weight materials (Benyus, 1997; Ball, 1998; Perkowitz, 2000).

We can also improve our manufacturing processes by studying nature. If we feed a chicken some grain, water and crushed eggshells it will produce an elegant plastic for quills and feathers. Writers for thousands of years used this quill plastic to make pens that are still preferred by some calligraphers. We are just starting to discover other opportunities for using this keratin plastic, which currently poses serious waste disposal problems in industrialized chicken production (Martindale, 2000). To reuse this plastic the feathers are dried, sterilized and shredded and separated in a density based air separator. The barb fibers which are stronger and more flexible are separated from the quill. The fiber powder has been used to make polymer films that may replace cellophane in food packaging. The powder is also excellent as a reinforcing fiber, replacing fiberglass fibers in mixes of other plastics. Five billion pounds could be produced every year in the U.S. if all feather waste was utilized. This would dramatically reduce pollutant loading to the environment and would save landfill space now lost to feather waste.

Spiders, which are older and even less biologically complex than chickens are also sophisticated material manufacturers. A spider given a few flies to eat can make a range of remarkable fibers at room temperature, again with no toxic wastes and very low embodied energy and minimal resource use. Recent studies have demonstrated that these fibers include small crystallites embedded in a flexible soft matrix (Ball, 1997; Thiel and Viney, 1995; Gosline et al, 1995). Dragline silk is several times stronger and tougher than Kevlar. The specific strength of dragline silk is five times that of steel, and when overloaded it can stretch 40% longer than its original length and still bounce back. A web of spider silk with strands less than a cm in diameter could theoretically stop a passenger jet in flight. From among the many tens of thousands of species of spiders only a few have been studied, and little is known about the different strategies used for manufacturing in different climates and the properties of the many fibers they can spin, including dragline, capture, anchor, support fibers, attachment silk and wrapping silk.

Mammals also develop remarkable composite materials in skin, bones, teeth and tendons. Many of these currently pose disposal problems, but may become resource streams. These mineral, keratin and collagen biocomposites can also provide models for strong, durable and yet easily recyclable bioengineered products for a wide range of uses.

3. Ecocomposites in history

The most elegant ecocomposites combine naturally occurring materials without extensive processing. One of the first steps in the ecocomposite revolution should be an effort to catalog and make available on the web the existing knowledge of historic and prehistoric fiber and resin use around the world (see for example, Whitford, 1941; Hickman, 1969; Morton, 1975; Shrijkata Rao, 1985; Ebeling,1986; Bernan Associates. 1989; Plastics Historical Society, 2001; Bainbridge and Lwin, 2001). One of the other important lessons we have learned recently is the value of local knowledge and adaptation to local environments (Nazarea, 1999). This may be important in our future efforts to develop locally adapted, ecologically sustainable production systems.

Four examples suggest the broad range of historical innovation in ecocomposites: the composite bow, linen armor, fiber reinforced earth homes, and the birch bark canoe.

Ecocomposite bows

Ecocomposite construction improves the cast of a bow. The most elegant and complex bows included a glue and sinew layer on the tension side and a bone layer on the compression side (Hickman, 1959; Miller et al., 1986). Sinew (tendon) is very strong and has superb strength and energy return properties. Collagen has a resilience of 93%, so there is a loss of only 7% when it is stretched to store energy (Vogel, 1998). Sinew can store 20 times more energy than steel on a weight basis. These composite bows enabled archers to shoot arrows up to a half kilometer in sieges and battles. The same technology enabled hunters and horse mounted warriors to use compact short bows instead of unwieldy long bows. Ecocomposite bows a meter long could compare favorably with all wood bows twice as long.

The bows are not more than two feet and a half in length, they are formed of a slip of red cedar; the grain being on one side untouched with any tool, while the other is secured with sinews attached to it by a kind of glue. Though this weapon has a very slender appearance, it throws an arrow with great force and to a considerable distance.

Alexander McKenzie, 1793.

Figure 1. Cross section of an Assyrian composite bow (after Hickman, 1959).

Fabric armor

Fabric armor has been used in many periods of history, but was common in early Greek times, where a linen armor known as linothorax was preferred. Multiple layers (20-30+) of linen were glued together with hide glue (or perhaps a sun refined oilseed varnish) to produce the ancient equivalent of bulletproof vests. A good set was as costly as bronze armor (Storch, 1998). The advantages of linen armor included lighter weight, improved mobility, and comfort--particularly when it was hot. A wide range of fabric armor made with linen or other fibers, often quilted and padded rather than laminated, remained in use for more than a thousand years. The Fraternity of Tailors and Linen Armourers of St. John the Baptist was instituted in London in 1272 and reauthorized by monarchs up to and including James I.

Fiber reinforced earth buildings

An adobe without straw is like a marriage without love. Traditional Mexican saying

The use of ecocomposites for building also extends far beyond recorded history. Straw or dung (processed fiber) reinforced clay or earth blocks or monolithic walls are found in most areas of the world in the archeological record, and are still used today by hundreds of millions of people. Straw was often used to strengthen monolithic mud walls built without frames or forms (Bee, 1997; Kawashima, 1986). Mud and clay with fiber was also used to help improve the properties of mud based blocks. As buildings became more complex, with wood frames, infill materials with good stability and some insulation value were used for wattle and daub and other wall systems (Powys, 1981). Reinforcing fibers might include straw, flax, other plant parts, or hair. The flax fiber reinforced daubs have remained strong and flexible after several centuries, while the straw eventually becomes brittle.

The light straw clay infill insulation (*leichtlehmbau*) of timber frame houses in Germany is a perfect example of ecocomposite use (Gibson, 1993; Volhard, 1995; Andresen, 2002). In this building system lengths of straw are coated with a very light clay slip that sets quickly after placing, stabilizes the mix, strengthens the wall and improves insect and fire resistance. The straw provides a matrix to retain air and provide insulation.

Figure 2. Light straw/clay house

The birch bark canoe

The birch bark canoe uses large sheets of bark from the birch tree, tree roots (often spruce) for sewing, a flexible frame of a strong light wood (often cedar), and a caulking material made of pine or spruce resin, improved with a range of additives. The birch bark can be obtained in big sheets from the tree and includes waxes which make it waterproof. Birch bark canoes may have been manufactured and used for 5,000 years in North America, and were also used by tribal people in Siberia and ancient Japan. The North American canoes were most highly developed. Their value was first recognized by Samuel de Champlain about 1600 (Huck, 2002). By 1785 two main types were being built and used. The *canot de maître* and smaller, *canot du nord*. The *canot de maître* was 10-12 meters long and with a crew of eight to twelve and a capacity of 4 tons. The *canot du nord* was 7-8 meters long with a crew of four to six men and a capacity of 1.5 tons. The smaller canoe could be carried by two men. Birch bark canoes played a critical role in Canadian development for almost 400 years.

All four historic uses illustrate the essential properties of ecocomposites in sustainable manufacturing systems. All four are elegant uses of natural materials, with sophisticated choices of materials made to achieve high performance at low cost. The workers who manufacture them are not exposed to toxic materials. The waste byproducts from manufacturing can be composted. Maintenance is required, but materials for maintaining these products are low cost and have little impact on the environment. At the end of use and maintenance a clay straw home will gradually melt into the soil, leaving little trace. An ecocomposite bow, linen armor, or chunks from an earth straw wall can be tossed onto the compost pile when they are damaged or too worn for repairs. A birch bark canoe will return to nature in a few years, providing nutrients for the growth of the birch tree that will provide the next sheets of bark.

4. The advantages of ecocomposite materials

Natural fibers compare favorably with man-made fibers on a strength basis and are attractive because they have chemically reactive surfaces which make more complete fiber-matrix bonding possible (Bolton, 1991). Flax (linen), hemp, coir and many other fabrics and fibers can replace more energy costly and less degradable fibers in a wide range of applications (Swamy, 1988; Anon, 1993; Lenox-Kerr, 1994; Hague et al., 1998; Rout et al, 2001; Head, 2001). Old varieties with better stem, leave or stalk characteristics may be rediscovered, or crop plants may be reengineered to provide more suitable fibers. This can add value to farm crops by diversifying the range of farm products for sale in addition to simply the grain, fruit or flower. This more closely approximates the historic farm practices where multiple uses were the norm. This reduces waste and minimizes the risk of pollution.

There are many opportunities for replacing high environmental cost materials with natural fibers and materials. Although hemp, flax or other fibers have been used to reinforce plasters and cements (Pacey and Cullis, 1986), the performance and use can be greatly expanded if appropriate sealers and primers can be found. A varnished hemp net for example might serve as a reinforcing fiber for concrete.

Ecocomposites made with natural fibers are being used more commonly in industry, particularly in automobiles (Herrmann et al, 1998: Lang, 2002;   ). Many of these are ecocompostite lite – with natural fibers and non-renewable plastics from petroleum. These can be hard to reprocess or recycle, but work is progressing on ecocomposites using all natural materials. This is the ultimate goal, materials that are clean, green, strong, easily maintained and easily recycled, reused or returned to nature.

Natural plastics have been used for many thousands of years and discoveries in recent years suggest they will return as critical components of a sustainable society based on industrial ecology. The traditional natural plastics and glues include materials like: keratin (hoof and horn), silk, natural rubber, gutta percha, paper maché, bois durci, shellac, lacquer, varnish, starch, isinglass, hide glue and hundreds (perhaps thousands) of other resins and saps (Bawden,1990; Huber, 1996; Mathias, 2001; Plastics Historical Society, 2001). These natural polymers include polysaccharides, peptides, enzymes, proteins and other complex molecules. The polysaccharides include both wood and sugar, which formed the basis for many early modern plastics including cellulose acetate and the highly flammable cellulose nitrate. Many of these very early cellulosic plastics are still used today, including Tenite™ acetate the first of the modern thermoplastics, created in 1929 (Eastman, 2001). Lignin, a plant biopolymer, has been used to make printed wiring board for the electronics industry (Kosbar et al., 2001). We now have sugar based epoxies that outperform petroleum based products for binding concrete, wood, metals, and plastics (Suszkiw, 1999). Ultimately many plastics may be bioengineered into crop species and grown, but not without risks, see the following section.

Many waste products are rich in raw materials for plastics and resins. Cashew nutshell resin is made from cashew nutshell liquid (CNSL), a mixture of phenolics extracted from cashew nut shells. CNSL is the only naturally occurring alkenyl phenolic material in world trade at the moment. Researchers at CBRI Roorkee developed a new process for making a CNSL coir and paraformaldehyde fiber board (CBRI, 2001). Researchers at the BioComposites Centre in Wales have found a way to make a formaldehyde free resin from CNSL that can be water sprayed. This resin could be used to make strong "bioboards" with no formaldehyde emissions (BioComposites Centre, 2001). There are also many promising, yet largely untapped uses for chitin, nacre and bone and tooth mimics (Daly and Macossay, 1997; Benyus, 1997; Ball, 1998).

Ecocomposite resins and fibers may be harvested or created (Imanishi, 1992; Coombs and Hall, 1998; Valigra, 2000). These new and old ecocomposites will be used for structures and goods, as well as for the repair and reinforcement of existing structures to offset deterioration caused by aging, meet new code requirements or improve seismic safety (as described for composites, see for example Meier, 1997; Ehsani et al., 1997; Kolsch, 1998; Valluzzi et al, 2001).

We can also learn many other lessons from nature. By carefully studying natural materials we may learn how to do low temperature manufacturing with simple materials and few waste products. This will be made possible by often very complex catalytic or enzyme reactions, replication using templates; self-assembly; structure and organization on many scales (from nano to macro); and control of nucleation and crystal growth (Baer et al., 1992; Heuer et al., 1992; Sarikaya, 1994; Benyus, 1997; Ball, 1998).

We also have a great deal to learn about harvesting, processing and preparing materials. Research and experience with natural fibers, now virtually forgotten, will prove very useful in this effort (Dodge, 1893; Kirby, 1963). Hobbyists have also developed a great deal of information on fiber use (Bell, 1988; Hiebert, 1998). Ethnobotanists may find themselves adding fibers, glues and resins to their research agendas (Martin, 1995). Designers would benefit from an ecocomposite data base comparable to MIL-HDBK-17. This would improve regulatory acceptance, procurement and specifications. Designers and engineers would also benefit from materials selection charts comparable to those championed by Michael Ashby (1994) at Cambridge University, but adding a wider range of properties, figure 3.

Figure 3. Material suitability charts

The great challenge for the future is developing production systems that mimic nature and use waste or renewable resources to meet most of our needs. Considerable progress has been made in some areas, but much remains to be done at the systems integration level. This high order organization has proved critical in optimizing solar and green building design and performance. It will also prove essential in reforming our manufacturing and building industries.

The first step is improving accounting for the true costs of materials and resources from the cradle to the cradle (McDonouhg and Braungart, 2002; Schaltegger and Burritt, 2000; Schaltegger et al., 2006). MIPs, Eco-it™ and other lifecycle and ecofootprinting tools help us determine the resource impacts of materials and products, but much more needs to be done to fully understanding their cost (Curran, 1993; Keoleian, 1994; Luttropp and Lagerstedt, 200?; Robèrt et al., 2002). Ultimately material impacts, ecosystem effects, embodied energy, water cost, pollution burdens, and health costs will be included in product literature so that designers, builders, manufacturers and consumers can choose wisely among competing products.

5. The sustainable future

The discussions of a more sustainable future have often focused on dematerialization, dramatically reducing material demand by a factor of 10 or 20. This may be helpful, but as McDonough and Braungart (2002) note, it is not necessary to reduce material used dramatically if we use the right materials. This can make the transition to a sustainable economy easier and faster. Ultimately the goal is to sustainable materials and systems that benefit the environment and help improve human health. If we do this the volume of material matters much less than the nature of the materials.

Likely candidates for early adoption include the use of ecocomposites in transportation, building and construction, furniture and fixtures, and transportation. A wide range of other uses will become feasible as the understanding of the creation, harvest, modifation and use of ecocompostie materials improves.

Ecocomposites in transportation

Mercedes Benz and other auto manufacturers are increasingly using natural fibers based ecocomposites in auto construction. Many panels are now made of flax and plastic. The headrests for many Mercedes models are made in Brazil using natural fibers and latex (Whitfield, 2001). The American Corvette sports car and many high performance boats often rely on balsa wood for strength at low weight. If these can be combined with natural fibers and resins the ecocomposite market will increase rapidly.

Ecocomposites in building

Ecocomposites for building can help meet the critical need for improved housing around the world while reducing the enormous environmental toll of the built environment. Detailed studies in Germany showed that buildings consume 25-30% of the total non-renewable material flux (Schmidt-Bleek, 19??). The environmental and financial cost of constructing, maintaining and operating building can be reduced by rediscovering ecocomposite materials (see for example, Elizabeth and Adams, 2000).

Adobe blocks have traditionally been reinforced with plant fibers, but Bill and Athena Steen's work on adobe blocks made with a much higher percentage of straw has been very encouraging (Anon, 1996; Steen and Steen, 2000). This improves the strength and performance of a traditional building material with a waste resource and is readily accepted by builders. The fiber reinforced clay used as infill in Germany may today be replaced with wood chips to make a denser material that is easier to handle and more economical (Andresen, 1997). Manufactured panels (500 x 250 x 100 mm) of this material are now available in the commercial market for new or retrofit construction. The earth reel roof system developed by the Swedish Association for Development of Low Cost Housing is also an innovative use of ecocomposites to meet a critical world need (Stulz and Mukerji, 1988).

Wood fiber reinforced concrete has a long and illustrious history. Developed under severe resource constraints after WWII in Europe the process of using wood fiber in cement based building materials in place of sand and aggregate is still in widespread use (Anon. 1998). Much of this product is used in wall forms that are used for poured concrete buildings. The forms can be stacked with limited skilled labor, rebar is inserted and the cores are then poured in four foot lifts. In Ontario, Canada they have been used for buildings up to 23 stories. No vapor retarder is needed because it can absorb considerable moisture without harm. These walls are favored by some builders because they breath well and are less likely to develop mold and moisture problems. Durisol panels are made in Canada primarily with construction wood waste, based on a process developed in Switzerland. A similar product, Faswall, has been manufactured in the U.S. using shredded pallets, but the manufacturers claim it could also be made with waste wood, agricultural byproducts, or green timber (Faswall, 2002). The secret for both has been patented mineralization processes to prepare the wood for use in concrete.

Straw is a very rich resource for ecocomposites, increasingly available as field burning of straw is banned (Bainbridge, 1986; Robson and Hague, 1993; PIRA International, 1993; Wasylciw, 2001).The pressed straw panels known as EasiWall from Stramat, used in England in many thousands of homes, are simply compressed straw with a paper facing. The Stramit process makes a strong 7 cm thick panel with no glue. The Alberta Research Council has done some excellent development work on straw board manufacturing, with costs competitive with wood fiber (Wasylciw, 2001). If subsidies were removed and full environmental costs were counted straw based products would already be used in virtually ever building constructed in North America and Europe.

Straw bale buildings reinforced with natural materials and plastered with straw or natural fiber reinforced mud can be used to build very energy efficient, durable and fire resistant structures (Bainbridge, 1986; Steen et al., 1994; King, 1996; Haggard et al., 1999; Lacinksi and Bergeron, 2000; Lerner and Goode, 2000; Magwood and Mack, 2000). Modeling of straw bale solar building performance suggests annual energy use for space conditioning in Denver, Colorado can be cut from 65,000 BTU/ft^2 to 800 BTU/ft^2 (Elizabeth and Adams, 2000). Straw bale buildings in Mongolia reduced energy consumption 80% (Lerner, 2002). Straw bale building is now entering the commercial building field in the U.S., with a large winery complex, 1800 m^2, now nearing completion north of San Francisco, a number of schools, a bus repair facility near Los Angeles, and a wide variety of other buildings. Commercial buildings in have been constructed in Australia using the very large straw bales, 1m x 1m x 2m, providing superlative thermal performance. King (2002) reports that the use of straw bales in buildings is increasing at 30% a year.

Wood fiber has been used to create "Bioblocks", in some ways similar to straw bale construction (Platts, 1996). **(more)**

Building materials made with natural fibers and recycled or natural materials can also be called ecocomposites, although perhaps the eco should be lower case or footnoted because they are often end of life materials that cannot be easily recycled or reused..Many of these are already in use including wood fiber reinforced cement siding (Hardie™ board and others) and wood fiber reinforced recycled plastic lumber (Trex™ and others). Linoleum, a once widely used ecocomposite made of linseed oil and wood fiber, is gaining favor as builders try to detoxify new homes.

Ecocomposites will become increasingly common as the price of energy, oil and lumber continue to climb, environmental problems with plastics disposal increase, and agricultural fibers pose increasing costly disposal problems (as field burning of rice straw is curtailed for example). The growing concern over indoor air quality will also encourage adoption of ecocomposite materials.

Ecocomposites in fixtures and furniture

Several companies already use ecocomposites in furniture and fixtures. The Phenix? Group has developed . Others manufacturers using ecocomposite materials include ____. The APT program in Zimbabwe has encouraged use of ecocomposite materials for fixtures, furniture and aids for handicapped people (Packer, 1995). The adoption of ecocomposite materials has been driven in part by the desire to improve indoor air quality and reduce risks of combustion byproducts.

The current municipal solid waste stream is a fabulous resource for ecocomposites for fixtures, furniture and more. Every year 230 million tons are thrown away in the U.S. (EPA, 2002). Many if not most of these wastes are suitable for ecocomposites, including 12 million tons of yard waste, 47 million tons of paper and paperboard, and 12.6 million tons of wood. Although 35% of plastic beverage containers are now recycled most of the plastic waste stream is not, and many plastics such as polypropylene are well suited for ecocomposites. Yard waste, paper, wood and plastics can be used to make natural fiber reinforced plastic lumber for decks, fences, roofing and trim, wall dividers, furniture, and eventually, perhaps, foundations.

6. Opportunity and Threat: Genetic engineering of ecocomposites

The ongoing worldwide controversy over genetically modified (GM) crops and microorganisms is likely to influence the future of biopolymers and “green” plastics made by genetic engineering. While this war has been muted in the U.S., it has been more strident in Europe, Asia, and India (Cummings and Lilliston, 1999; Raj, 1999). Like most environmental controversies it involves complex and poorly understood science and economics, widely differing cultural values, and increasing polarization between industry's Panglossian view that "this is the best of all possible technologies with virtually no risks", and the Doomsayers view that "this is the worst of all possible technologies with catastrophic risks." No one knows who is correct – the research has not been done.

Despite the very rapid increase in the acreage of GM crops in the U.S., 45% of soybeans in the U.S. by 1998 according to some estimates, the ecological, economic, and health risks of these crops remain poorly understood and little studied. Ecologists have been long been concerned about a range of possible problems including: the evolution of resistant pests, risks to non-target organisms, creation of super pests by hybridization or gene transfer, and changes in farm management with attendant ecological consequences (Gould, 1988; Tiedje et al., 1989; Rissler and Mellon, 1996: Snow and Moran Palma, 1997: 2006). Doctors are increasingly concerned about possible health effects (Nestle, 1996; Bindslev-Jensen, 1998).

The use of GM to create biopolymers and chemicals for ecocomposites carries with it the risk of contaminating food sources with inedible or poisonous compounds. If carefully managed and wisely used GM crops hold some promise in reducing use of biocides and protecting the environment. But there are also many very real concerns about the impacts of plants with engineered resistance on organisms that are neither beneficial or harmful, as part of the continued erosion of ecosystem biodiversity (Nabhan, 1999). These impacts are little studied and yet perhaps the most important issue in the debate.

Creation of super-pests is also a very serious concern. This can occur from hybridization of crops with wild relatives or from genetic recombination, which "in nature is neither so rare that we can ignore its occurrence, nor so common" (Tiedje et al., 1989). Crosses between herbicide resistant crops and wild relatives (rape is a good example) are likely to create weeds which are increasingly difficult to control (Mikkelsen et al., 1996; Kling, 1997). There are also concerns about virus resistance spreading to weed species (Coghlan, 1998). These may prove even more costly than exotic weeds, which have been serious enough (Bainbridge, 1997).

Genetic transfer between organisms may help create new antibiotic resistant bacteria that will challenge farmers, veterinarians and doctors. The widespread early use of antibiotic resistant markers to identify GM crops has declined, but should never have been started. GM work on producing biopharmaceuticals in food crops is extremely risky and should perhaps be banned. GM for ecocomposite material development may also introduce chemicals into plants that are harmful or fatal to a wide range of organisms in the target plant and in related wild relatives and choices of production species should be very carefully made..

Although these new pest resistant GM crops are often touted as ecologically benign and far safer than biocides little data is available to support or reject this claim. What we do know, and should admit, is that we don't know. Surprisingly little research is underway to resolve these important questions. Many of the important findings have been made by curious scientists or NGO funded studies, while the governments and GM manufacturers have tended to fund efforts to rebut criticism rather than searching for potential problems with careful, systems oriented long-term interdisciplinary research.

Many of the unresolved questions about GM crops are economic, including the costs of possible damage, the benefits of use, and the issue of who would bear the liability for the potentially enormous costs of foreseeable catastrophes. Unlike the costs of pesticide induced problems, which were never properly charged to those responsible, it is likely the costs of the escape of superweeds, superpests, and the squandering of valuable biological resources such as the Bt toxin will be determined as the sophistication of economists has increased substantially (Bainbridge, 1983; Goodstein, 1995; Kahn, 1998). The Bt toxin is a public resource which behaves much like an open access resource, without government intervention it will be eroded away just as fisheries stocks have declined. The rapid growth of the organic food market and the increasing sophistication of growers has made it time for a careful reappraisal of a question first explored by Langley et al. (1983). They concluded that a total conversion to organic farming would increase net farm income as a result of decreasing input costs and rising prices.

The controversy in many respects mirrors previous problems from the misuse of biocides, and it is clear that industry (and to a lesser extent) regulators have learned little from the experience. More money will probably be spent on public relations campaigns promoting GM organisms than is now spent on interdisciplinary long term ecological research. In the U.K. a PR campaign by the government for GM crops backfired after internal documents were leaked to the press, and the Ministry of Agriculture, Fisheries and Food adopted a fairly conservative position (MAFF, 1999). This still may not be enough, as polls in England and Europe show that people want GM foods labeled (95% in Denmark) or banned altogether (68% in Denmark) (Parkins, 1999). In England a poll by the Express showed 94% wanted them banned. Austria and Luxembourg have banned GM crops and foods despite EU pressure. The EU was forced by public opinion to adopt a weak labeling scheme. The victims of the current rush to embrace GM crops are likely to be the American farmers whose markets are increasingly being restricted by Asian and European requirements for non-GM varieties or GM labeling.

The tragedy is that potentially very valuable opportunities for using GM organisms will be lost because of sloppy and careless development work without sufficient research and caution (Bainbridge, 1999; Simon, 2002). To protect these resources I support a greatly expanded program of long term ecological and health research on GM organisms, a pause or at least slowdown in rollouts and use, and a much more careful accounting of all the costs and benefits of GM crops compared to conventional organic and mechanical pest management. The use of non-food crops for chemical production should also be encouraged, despite the seemingly "easier" use of food crops that are well understood.

I would also suggest the major biotech firms should adopt a more humble and conciliatory approach. Labeling is essential and non-negotiable. As the President of Novartis, the Swiss biotech, said in 1996, "if we believe in the consumers right to choose, the industry cannot argue against labels facilitating this choice." As a person with serious multiple food allergies, labeling matters to me much more than to the average consumer, but it also matters to the several million other Americans with food allergies (Nordlee et al., 1996; Nestle, 1996). Few of them would willing choose to die so that farmers can produce slightly cheaper foods. Current testing is dreadfully inadequate.

As the Ecological Society of America commented in 1989, "For society to realize the full benefits of biotechnology, interdisciplinary research and graduate training programs are needed to expand the expertise of the scientific community at large". The National Science Foundation and the U.S. Department of Agriculture should encourage a more thoughtful and cautious approach to the introduction and use of GM organisms and crops. Testing must be removed from corporate control and secrecy to public research and publication in peer reviewed journals. N.S.F. and the U.S.D.A. could also help ensure that funding is available for training of biologists, biological engineers, geneticists, ecocomposite materials engineers, agronomists, economists and ecologists provides the needed skills for this important work.

As Adam Smith said, "*Science is the great antidote to the poison of enthusiasm and superstition*. If we fail to bring science into the discussion, the critics will have been proved right again. The holy crusade for GM crops will run into an equally determined and misinformed crusade against all GM crops and Society may lose some potentially very valuable resources for producing ecocomposite materials.

7. The future is now

Business ecology is predicated on the understanding that, in order for business to be ecologically sustainable , it must learn about, integrate with and adapt to the ecosystems of which it is a part and upon which it is fully dependent. Amy K. Townsend (2005)

The age of composites is well underway. With appropriate attention to the opportunities in natural fibers, glues, polymers, and resins the transition to a Society based on safer and more environmentally friendly **ecocomposites** can be made. Agroecology, industrial ecology and bioengineering should make it possible to grow and process these materials economically and safely in sustainable farming systems (Mitchell and Bainbridge, 1991; Graedel, 1994; Gliessman, 1998; Rotman, 1998; Bainbridge, 2001). These materials can be used to make lighter, stronger and more durable products that conserve non-renewable resources and energy and improve human health. Long life and eventual recycling can be engineered into these products, adding the fourth R to "Reduce, Reuse, Recycle" -- "Return to Nature".

The development of sustainable agro-industrial ecosystems is also overdue. This will require integrated scientific, engineering, and financial analysis using the most advanced tools of landscape ecology, agroecology, ecological economics and industrial ecology. The goal will to be to maximize benefits across a wide range of considerations, from biodiversity to aquatic health to economic resilience. Crops with multiple uses and resource streams will probably prove most useful. Industrial hemp for example can provide fiber, hurds for wall systems, and seeds for food or oil. These and other plant oils can be used to create resins, plastics and other ecocomposite matrix materials.

Cropping systems can also be developed to maximize benefits and minimize impacts of primary food crops. Rice production, for example, can provide the rice for food, rice straw for fiber, paper, straw reinforced building panels and materials, rice hulls, rice hull ash (a good pozzolana for plastering and cement); and utilizing the straw reduces production of the global warming gas methane from flooded fields after the harvest (Bainbridge, 1993; Steen et al., 1994; Bainbridge et al., 1996; King,).

We must also focus our attention on multifunction production processes for fiber and resins. Biological waste treatment in constructed wetlands has proven to be economical, safe and effective (Jewell, 1994). These wetlands can produce large quantities of reeds (*Phragmites*), sedges (*Carex*), cattails (*Typha*), bulrushes (*Scirpus*) and rushes (*Juncus*); all excellent raw materials for ecocomposites. Initial research in Estonia has demonstrated the potential of this approach, with cattail fiber reinforced mud blocks proving to be very strong (Suursild, 2001).

Ecocomposites will usually be safer to handle and work with and more environmentally friendly than synthetics. Most can be recycled (composted or digested) or burned, without the residues that are left with plastic and silica based fiber composites. The raw materials for ecocomposites can be produced by sustainable agricultural systems, with low embodied energy, with atmospheric carbon rather than mined "carbon" from petroleum or coal (see Mitchell and Bainbridge, 1991; Gliessman, 1998; Altieri, McDonough and Braungart, 2002). We can also learn full recycling and reuse of materials, developing an industrial systems that mimic natural ecosystems and are efficient clean, safe and economical (Graedel and Allenby, 1995; Erkman, 1997). Comparable work in Europe led to the development of the Kalundorg industrial complex in Denmark, matching waste streams to input requirements of other industries (Jacobson, 2006).

Some furniture and fixtures for the home and office are already made of recycled materials or waste materials. Sadly, many of these are not recyclable or reusable: but they could equally easily be made of ecocomposites. It is already possible to imagine a biodiesel powered bus built from ecocomposites and lubricated with vegetable oil based greases and oils. It is not much harder to envision a sport airplane built of ecocomposites, running on biofuel.

The economic benefits of using ecocomposites cross many sectors of the economy of both developed and developing nations. They include: the production of natural fibers and resins in farming areas beset with economic and environmental problems, reduced environmental costs of manufacturing and waste disposal, and savings in health care costs and environmental cleanup. The introduction of natural fiber based materials can reduce global warming (sequestering carbon), improving energy efficiency (reducing energy use and air pollution) and limiting consumption of non-renewable resources. Even before the conversion to biopolymers and green plastics is complete the combination of natural fibers and recycled plastic can absorb part of the plastic waste stream, and improve the energy efficiency of homes and commercial buildings (Lampo, 1995; Packer, 1995; Bainbridge, 2001).

This is an exciting new frontier that requires the talents, skills and enthusiasm of engineers, chemists, materials scientists, botanists, biologists, mycologists, agronomists, anthropologists, archeologists, historians and ecologists. This will require new incentives for inter- and trans-disciplinary research and creation of data bases of natural fiber and resin properties and processing approaches. These can build from the limited information currently available (Brady et al., 1997;   ). It might best be done in a Wiki format to enable contributions from around the world. This will speed the transition, not only in the industrialized countries; but also in developing countries where the potential applications are perhaps even more important.

Industrial ecologies are designed to fit into the landscape without harming the environment and to minimize use of both renewable and more particularly, non-renewable resources. The basic approach is to consider the industrial, manufacturing, disposal/recycling process a closed system much like a natural living ecosystem. Materials, energy and water and other resources are used, recycled and reused with minimal leakage into the environment or movement into landfills.

The rapid growth of the internet and global connectivity has made this much more practical. Users and waste generators can link up in a local, regional, national and global web. Individual companies, like organisms in an ecosystem, can work for their own survival and prosperity while benefiting the environment. This movement is also benefiting from the increasing sophistication of accounting for environmental and health costs. As the "polluter pays" principle is more widely adopted the incentives for participating in industrial ecology networks become much greater. In fact, if true cost accounting was done, the industrial ecology approach would be universally adopted.

One of the more important aspects of industrial ecology is minimizing waste. This will remain true in an ecocomposite based industrial transformation. A key component of this effort is finding consumers for waste, as the old saying goes, "One man's garbage is another man's treasure." Kalundorg, Denmark is an early adopter of this approach (Jacobson, 2006). Industrial ecology facilitates the use of fewer “virgin” resources and consumes less non-renewable energy and resources. The goal is to provide the same level of production, comfort and improved quality of life at much lower cost. Compare for example a record player of the 1940s with an Ipod today. Less material, perhaps 1% or less, but improved performance. Value and productivity are enhanced by improved information, knowledge and technology—not by increasing mass or energy use. The continuing increases in GNP while energy use per capita declines reveal the beginning trend, but much remains to be done (decoupling article).

The U.S. should develop a comprehensive program to hasten the transition to a clean, efficient economy by supporting increased work on true costing of resources (ecological economics), industrial ecology, use of wastes for product creating, use of biological systems for waste processing and development of improved tools for calculating the true life cycle cost of materials, products, operation, maintenance and disposal. Industrial ecology would benefit from a transition from the burdensome prescriptive regulations currently used to keep pollution at an acceptable level, to a performance based approach that encourages innovation and minimal resource use and pollution (Andersen, 1994). As George S. Patton said, "*If you tell people where to go, but not how to get there, you'll be amazed at the results*". That is what financial incentives do so much better than the prescriptive regulations typically adopted for pollution control.

Many European countries have adopted a performance based approach with financial incentives and seen results ( ). This has stimulated creative solutions and reduced waste and pollution. The Netherlands used this approach to clean up waste water. At virtually no cost to taxpayers they went from one of the poorest managers of waste water to one of the best, reducing pollution below the levels reached with very high government (tax based) spending in Denmark and Germany (Anderson, 1994). This has also worked well in the chemical industry – which might seem the most resistant to change (Erkman, 1995). At the Rhone-Poulenc plant in Chalampe, France the nylon process was changed to eliminate a problem with diacids –which had been burned. New equipment recovered these in a more useful form so they could be sold as additives for dye and coagulation, bringing in 20.1 million francs a year. This is the goal of environmental design—making industrial ecosystem run as efficiently as natural ecosystems.

Financial incentives work and will be essential to encourage the widespread adoption of industrial ecology in manufacturing and waste management. Pollution has been subsidized and encouraged for too long. If we provide people with more complete information they will make better decisions and we will all benefit.

The development of integrated, industrial ecosystems with full accounting for internal and external costs of material use will be essential to recognize the full potential of these ecocomposite materials. It will also require a much more complete analysis of product life cycles, material balances and life cycle cost and value. By working together, beginning with this meeting we can hasten this transition and improve the performance of ecocomposite materials by learning from past uses, successes and failures. The funding would logically be taken from existing agricultural subsidies, beginning at $500 million dollars a year and increasing until subsidies are eliminated and new markets for ecocomposite materials offer farmers new and sustainable markets.

Acknowledgements

With special thanks to Aung Zayar Lwin, Ton Peijs, Bill and Athena Steen, David Eisenberg, Bob Bolles, Bruce King, Ken Haggard, Polly Cooper, Kelly Lerner, Joe Kennedy, Lynne Elizabeth, Matts Myhrman, Judy Knox, DWB, and the many others who have provided encouragement, information and the opportunity to learn more about ecocomposites and ecological building practices. Many researchers, designers and writers around the world responded to queries in a timely and gracious manner, thank you.

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Figure captions

Figure 1. An Assyrian composite bow

Figure 2. Light straw clay building (photo)

Figure 3. Ecocomposite material selection charts

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Acknowledgments: Add London prof, Valerie Okerstrum,

www.ecocomposite.org

International Society for Industrial Ecology
www.yale.edu/is4ie/

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