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The application of ecosystems services criteria for green building assessment

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Abstract

In the discussion of environmental architecture, we are conjoining two disciplines, the subject of architecture and that of ecology. At their best, green buildings are examples of applied ecology, where designers understand the constitution, organization, and structure of ecosystems, and the impacts of architecture are considered from an environmental perspective. By utilizing the concepts, methods, and language of ecology, designers can create architecture that intentionally engages the natural systems of a site.

The establishment of assessment criteria implies the definition of building design criteria. If we establish criteria that are based on our best scientific understanding of environmental capacity, we will begin to develop a building stock that is sustainable. To do this we must quantify the link between the resulting environmental impacts and their cause in building production and use. This is not done in traditional building environmental impact assessment methods, which are based on quantifying assumed negative impacts of man-made interventions on the natural environment, typically using a code compliant reference building as a standard to improve upon. These indexes lack an ecologically derived baseline, or standard of measure, under which sustainable developments can be analyzed and compared on a universal basis.

An ecologically derived baseline can be used to measure negative impacts as well as positive impacts of buildings. It also allows vastly different project types, sizes and locations to be compared on an equal basis. This study extends the concept of ecological capacity into an architectural context, and develops carrying capacity as a time and area dependent tool to evaluate the effectiveness of environmental building design. The ecosystem services criteria study uses an objective metric of carrying capacity as an ecologically derived baseline (hectare/years) to assess building sustainability. The farmhouse, a low energy, biological material based building located in Boulder, Colorado is evaluated to show the application of this method. The relative ecological impact of energy and materials for this project is described, as well as identification of effective strategies for reducing environmental impacts of typical buildings.

Keywords: Ecosystem services; Green building assessments; Sustainable architecture; Carrying capacity; Ecological footprint

1. Human carrying capacity as a measure of environmental impact

Sustainable design at this moment in time remains a “good neighbor policy”, in that it is a choice in which our actions benefit our global neighborhood as much as they do our selves. This was poetically articulated in

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Garrett Hardin's seminal thesis "The Tragedy of the Commons", which amongst other points illustrates that the success of sustainability is rooted in an awareness of the interdependence of our community.

Since the earth has finite material resources and biological capacity, humans must live within the carrying capacity of the earth. As we exceed the carrying capacity of the earth's ecosystems, over time they are stressed, then go into decline, and finally collapse. They are expended rather than renewed. The construction and operation of buildings contributes to these environmental loads. Those who design and purchase buildings, however have no methods to assess the environmental impacts of their actions.

1.1. Other sustainable building indices

Several assessment indexes that are specific to buildings have emerged in recent years. The Building Research Establishment Environmental Assessment Method (commonly referred to by its acronym BREEAM) was launched in the UK in 1990 to provide an environmental assessment and labeling scheme for buildings (Baldwin et al., 1998). BREEAM, a voluntary market-oriented assessment of a building's environmental performance allows licensed assessors to perform assessments to maintain a consistent level of quality and objectivity. Buildings are assessed for both construction and operation. Metrics include environmental impact, energy efficiency, and health. Assessments are scored in terms of "credits earned" for good performance on water conservation, carbon dioxide emissions, etc. In the USA a similar assessment system is known as "Leadership in Energy and Environmental Design" or "LEED". Internationally the Green Building Tool (GBT) is an evolving assessment system sponsored by National Resources Canada that has generated substantial interest.

These scoring systems each use code compliant built environments as baselines to evaluate the environmental performance of the building being assessed. This skews the evaluation and has no correlation to environmental impacts. No indicators of environmental health are measured to assess the effect of a building. For example, using LEED, it is possible to construct a "gold" rated building of 250,000 square feet and a small 25,000 square foot "silver" rated building. The large building will have a better environmental rating, but will also have a larger environmental impact. In addition, many of the evaluation criteria in these systems are either subjective or difficult to quantify (e.g. "site selection"), or have tenuous relationship to environmental impacts (such as "views").

Another category of assessment methods are referred to as nature-based checklists. This includes Malcolm Wells' "wilderness-based checklist", the "net positive change" analysis, and the "Tadoseec" checklist. These methods all share the concept that natural systems provide services we desire, and we should rate our interventions for their ability to also provide those services. In addition, each of these checklists provides the ability to rate an intervention positively as well as negatively, setting the stage for regenerative design rather than only reducing impact.

These checklists are less developed than the other methods listed above and are not in wide use. However, they have the advantage of being design oriented, i.e. providing direction and information for designers in the design stage. They are also simple, and do not require extensive research or expense to complete. On the other hand, they lack quantification and they inherently bias towards no intervention as being "best".

1.2. The concept of ecosystems services

> *"In amnesiac revelry it is also easy to overlook the services that ecosystems provide humanity. They enrich the soil and create the very air we breathe. Without these amenities, the remaining tenure of the human race would be nasty and brief" (*Wilson, 1992*).*

Ecosystems goods and services are the benefits that we derive from the different functions of ecosystems. Ecosystems services are critical to the functioning of the earth life-support systems since they contribute to human welfare both directly and indirectly (Fig. 1). Most human endeavors depend on ecosystems services to some degree.

Ecosystem services are interconnected and interdependent, yet it is possible to identify individual critical impacts caused by building construction and operation. Buildings utilize the raw materials generated through ecosystem services and depend on the waste assimilation and climate regulation provided by ecosystem services. We are now exceeding the capacity of the earth's eco-

Gas regulation	Water regulation	Soil formation	Pollination	Food Production
Climate regulation	Water supply	Nutrient cycling	Biological control	Raw Materials
Disturbance regulation	Erosion control and soil retention	Waste treatment	Refugia	Genetic resources

Fig. 1. Some ecosystem goods, services, and functions (after Costanza et al. (1997)).

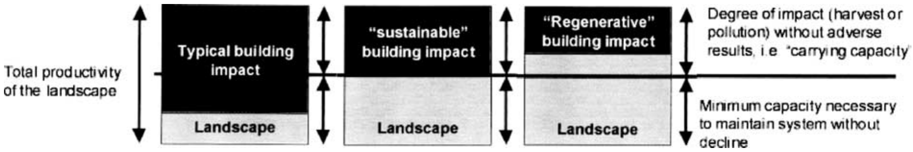

Fig. 2. Indices of building sustainability of 1.5, 1.0, and 0.5 respectively.

systems to assimilate the CO_2 we generate, as evidenced by global warming. In the USA, buildings consume 68% of the electricity produced annually, 75% of which is generated through the combustion of fossil fuels. The significance of this impact requires its measure; quantifying this metric insures that the majority of the environmental effects are accounted for. The energy consumed in the construction and operation of the buildings and the subsequent generation of CO_2 and its sequestration are the primary ecosystem services measured in this study. In other context, additional ecosystem services may be critical, such as water supply in dry climates.

We can measure the ecological carrying capacity of a given site and quantity of various ecosystem services on a specific site. Similarly, we can measure our consumption of natural resources (in this case specifically, those used for the production and operation of buildings) and calculate degrees of environmental impact based on ecosystem consumption. By comparing these two metrics, ecological resources and building impacts, we can rationally assess the environmental impacts of buildings. This method is based on the "ecological footprint" carrying capacity baseline as defined by Wackernagle and Rees (1996).

2. Evaluation method and metrics

Using ecosystem services as a baseline, a dual-criteria frame can determine sustainability. First, the quantities of ecosystem services are consumed in the production, products and use operation of a given building are reviewed. The assessment can be measured in (ecosystem productivity)*(land area)/(year). Second, it is important to consider the amount of land assigned to the project. The less land consumed per unit constructed is a strong measure of ecological efficiency. Two metrics are thereby generated; the index of building sustainability (IBS) and the index of efficiency in sustainability (IES). These two metrics can be applied to assess both construction and operational impacts.

2.1. The index of building sustainability (IBS)

The index of building sustainability (IBS) is the fraction of the annual carrying capacity of the project's land that is consumed by a building. An assessment of IBS 1.0 would meet the carrying capacity of a site and IBS 0.5 would use half of the available site ecosystem services, where as IBS 1.5 would exceed the carrying capacity of the site and is therefore not sustainable (Fig. 2). The IBS is a fraction and has no units; however, in application it can be considered a unit of time. For a single impact, an IBS of 0.5 is equal to 1/2 year of ecologically productive site capacity.

While the size of the site may seem to be an arbitrary measure to use to determine sustainability, it typically defines the extent of the owners' control. The IBS metric is thereby an indicator of the individual's relationship to the community, and shows their environmental obligation or contribution. In addition, inclusion of the site in these calculations provides the ability to incorporate the designers' restoration of local site ecology as a positive impact.

2.2. Index of efficiency in sustainability (IES)

The index of efficiency in sustainability (IES) is the quantity of land required to meet a sustainability index of 1. The less land required to meet sustainability index of 1, the more ecologically efficient the building is (Fig. 3). The IES is a measure of land area, and may use acres or hectares as its units.

Building impacts can be reduced through careful design and selection of materials that increase the ecological efficiency of the product. On the supply side, it is possible to use building construction as an opportunity to rebuild ecosystems, thereby increasing the ecological productivity of the site and reducing its impacts as measured by the IBS.

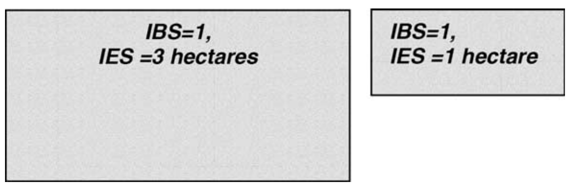

Fig. 3. The index of efficiency in sustainability.

Materials				unit	quantity	assumption	energy	unit	mj/unit	total mj	total GJ	GJ/ha/yr	ha	acres
	DIVISION 3													
03300	Cast in Place	foundation walls and slab	new	cy	61	150lbs/cubic foot	1.9	mj/kg		71120.45455	71.12045455	100	0.71	1.76
03300	Gypcrete	int. decks	new	cy	32		1.9	mj/kg		37309.09091	37.30909091	100	0.37	0.92
03300	Durock	walls for tile	new	sf	210	as sheetrock	4.4	mj/kg	70	14700	14.7	100	0.15	0.3632449
03300	Cast in Place Sink	kitchen	reused	sf	15		1.9	mj/kg		647.7272727	0.647727273	100	0.01	0.0160057
									DIVISION 3		**123.78**	**TOTAL**	**1.24**	**3.06**
	DIVISION 4													
04810	unit masonry	faswall	bio	sf	80	18	0.24	kW/block		34.09090909	0.034090909	100	0.00	0.00
04810	unit masonry	woodbrik	bio	sf	60	10.25	0.2	kW/block		23.29545455	0.023295455	100	0.00	0.00
04810	unit masonry	cmu	new	lbs	6050	55 lbs /sf	0.94	mj/kg		2585	2.585	100	0.03	0.06
									DIVISION 4		**2.64**	**TOTAL**	**0.03**	**0.07**
	DIVISION 5													
05120	structural steel	beams	reused	lbs	5409		10.1	mj/kg		2458.636364	2.458636364	100	0.02	0.06
05520	aluminum	trim,etc	reused	lbs	400		170	mj/kg		181.8181818	0.181818182	100	0.00	0.00

Fig. 4. Sample of CSI based environmental capacity construction impacts spreadsheet.

3. Evaluation of the farmhouse

Use of ecosystem services as green building evaluation criteria is straightforward. It requires three previously identified metrics for assessment: (1) construction impacts; (2) operational impacts and (3) site capacity.

Construction impacts are divisible into the material and energy components, which consist of subcategories. We have used standard Construction Specifications Institute (CSI) Divisions for tracking materials impacts (Fig. 4).

Site capacity consists of the initial assessment, any effects (typically deficits) incurred through construction and the addition of any capacity as provided through the generation of supplementary ecosystem services on site. Ecosystem services must be contextually defined relative to impacts (i.e. building construction and operation impacts consist largely of material and energy consumption and production of associated waste [largely CO_2]). Therefore, ecosystem capacity to absorb waste is an appropriate metric. This metric provides several key elements. Using ''global average productivity'', we can assess our impacts against an ''earth share average'' of consumption. The assessment depicts the impacts relative to total global capacity, and is most useful for an ''apples to apples'' comparison of significantly different projects. Using site-specific values of ecosystem productivity we can generate a regionalized assessment. Regional specific data allows for the possibility of restoration of local ecosystem productivity with the accompanying decrease in negative environmental impact. This is inherently more accurate and relevant to context. Once these quantities are established, an ecological ''proforma'' can be created, which shows return on investment, ecological profit, ecological deficit or ''mortgage'' created during construction, and time required to break-even, etc. Many types of economic analysis can be analogously ascertained using this instrument.

To demonstrate, the farmhouse, a low impact home/office built in Boulder, Colorado, is evaluated using ecosystem service impacts criteria. The farmhouse is larger than a typical residential building (530 m^2), as it performs as a residence as well as an office. Residential space occupies 230 m^2 square feet of the building, while the remaining 300 m^2 are used as open office workspace, shop, and model building area.

To normalize the results, the following metrics are compared on an absolute basis and a per unit area basis. A global average ecosystem productivity was used to measure carrying capacity. This quantity of land required to absorb the waste of the materials and energy was taken from Rees/Wakernagel, and assumed to be100 GJ/ha/yr. Most material impacts are translated into the energy embodied in the materials with additional land areas required for the production of the renewable materials used (Stein, 1981; American Institute of Architects, 1997). ''Typical'' reference building impacts are from Milne and Reardon (2003). These results are preliminary and will be refined as the data set is developed.

3.1. Evaluation of construction impacts

Impacts for the construction impacts are calculated as follows:

$$\begin{aligned}&\text{Material (quantity)} \times \text{(embodied energy)}\\&\quad /(\text{ecosystem productivity in GJ/ha/yr})\\&\quad = \text{ecosystem services consumed (ha/yr)}\end{aligned}$$

When compared on a per square foot basis, the farmhouse has 40% less energy embodied in its construction than a ''typical'' building. Total construction impacts amount to approximately 1800 GJ for the farmhouse, and 1000 GJ for a typical residence. This translates into 45.6 and 24.7 acres respectively (these are their IES numbers). This means that the ecological impact (deficit) from construction of the farmhouse can be recovered by the ecological productivity of 45.6 acres of land for one year's time. As a time/area measure, it is equivalent to 91.2 acres for 1/2 year, 1 acre for 45 years, or 152 years (its IBS number) on its 0.3 acre site.

Construction impacts are an order of magnitude larger than annual operating impacts, and will typically exceed site capacity many times. However, construction impacts only occur once, and in this way resemble an environmental mortgage which can potentially be repaid over time with efficient building operation and productive landscape.

3.2. Evaluation of operational impacts

Operating impacts were calculated by a similar procedure, using utility bills to determine energy consumption. When compared on a per square foot basis, the farmhouse is 70% more efficient to operate than a ''typical'' building (Figs. 5 and 6, and Tables 1–3). This is a significant reduction in environmental impact when

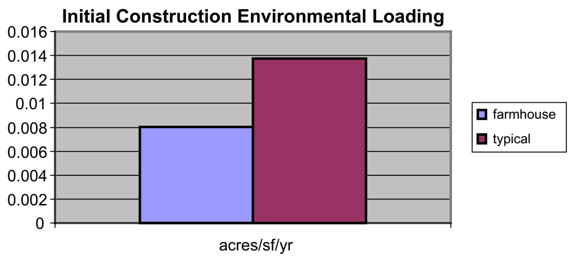

Fig. 5. Construction impacts.

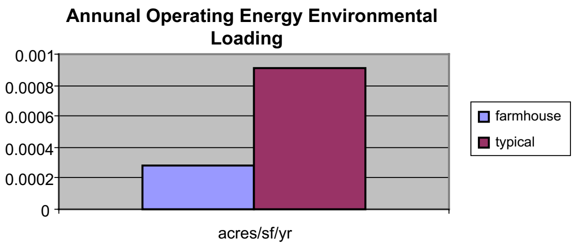

Fig. 6. Operational impacts.

Table 1
Summary of IBS and IES results

Building	Construction impacts		Operational impacts	
	IBS	IES (acres/yr)	IBS	IES (acres/yr)
Farmhouse	152	45.6	5.3	1.6
Typical	80	24.7	5.5	1.65

Table 2
Construction impacts

Materials budget	GJ	GJ/ha/yr	Hectares (ha)	Acres/yr
Farm house	1847.98	100	18.48	45.68
(per sf)	0.324206		0.0032421	0.008
Typical house	1000	100	10.00	24.71
(per sf)	0.555556		0.0055556	0.013
			0.42	Savings

compared to a "typical" conventional residence. From this analysis, the farmhouse on 0.3 acres of land is shown with an annual operating index of building sustainability (IBS) of 5.3 and an index of efficiency in sustainability (IES) of 1.6. This means the farmhouse would require approximately 1.6 acres of land (of global average productivity) annually to accommodate its ecological impacts. Because it is located on 0.3 acres, it exceeds its capacity by 5.3. While these numbers still exceed our goals, they show the significant savings achieved by the farmhouse, and point the way to designing and assessing higher performance buildings.

4. Life cycle space: the relationship of embodied energy and operational energy

4.1. Relative impacts

The operational energy of a building over its lifetime is typically much greater than the energy embodied in its construction. Reducing environmental impacts of buildings requires increasing the ecological efficiency in both construction and operation. According to Milne/Reardon, (Fig. 7), a typical residential building's construction energy is equal to 15 years of operating energy. In the farmhouse, the construction impacts are lower per unit and the operating energy required is even lower, extending the equation to take approximately 28 years of operating costs to equal the construction impacts. As operating costs go down, construction impacts increase in relative importance.

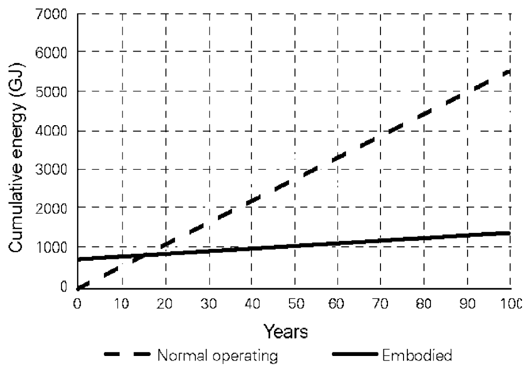

Fig. 7. Typical residential building operating energy impacts are greater than embodied energy over time.

Table 3
Operational impacts

Annual energy budget	kW h	GJ	GJ/ha/yr	Hectares (ha)	Acres
Farm house	17971	64.70	100	0.65	1.60
(per sf)	3.15	0.01135		0.0001135	0.0002805
Typical house	18500	66.66667	100	0.67	1.65
(per sf)	10.29	0.037037		0.0003704	0.0009152
				0.69	Savings

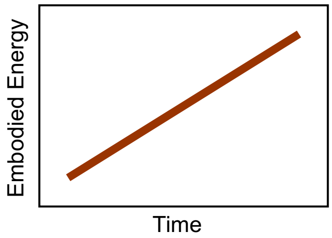

Fig. 8. As embodied energy increases, durability should also increase.

4.2. Durability

Another implication of this is the more energy put into construction, the more durable the building should be in order to realize the value related to environmental cost (Fig. 8). Ephemeral buildings, such as tents and igloos, which have extremely low embodied energy, do not incur significant environmental liability due to their short life spans. From this it is evident that long life buildings cannot be simply equated with responsible sustainable design, they still must be evaluated to assess their ecological cost, albeit with a longer potential return on investment.

4.3. Towards a restorative architecture

Current design knowledge and technology allows designers to produce high performance buildings that have minimal or negative operating energy requirements. "net zero energy" buildings and "net energy producing" buildings are becoming more common; clearly, the reduced operating impacts of these buildings allow them to potentially operate within the carrying capacity of the site area. Construction impacts; however, are likely to be greater in magnitude than the site capacity. In other words, construction "borrows" capacity from our global ecological store, the earth's accumulated ecological capital.

Architecture is not designed to be restorative and even minimal or zero operational energy costs have construction impacts. Ecosystems primarily use autotrophic systems to capture solar income and transform it to biomass, and build increasing complex systems, containing stores of energy, sinks, and regulated flows. If as part of a construction project site ecological capacity is increased, it might make the operating impacts less than preconstruction site capacity, creating a net increase in ecosystem services. Increasing available moisture, moderating temperatures, augmenting soil chemistry, or changing biotic material are all methods that may increase the ecological productivity of a site.

A second method is to include autotrophic qualities in the built environment. If a building produces more energy than it requires for its operation, it can augment the capacity of other interventions in the network. By displacing the need for additional ecosystem services, the services are "virtually" provided, and can be considered restorative. Photovoltaic materials can be considered autotrophic, as their embodied energy accounts for approximately 5–10 years of their energy productivity, after which they begin to generate more energy than was required for their manufacture (Knapp, 2000). Employing the autotrophic qualities of biological and mechanical systems, we can approach a restorative architecture that repays ecological debts due to construction, and eventually contribute to a sustainable environment.

Designing to meet sustainability can now be seen in a context that balances environmental impacts with the time required for ecosystem services to be generated, and the space required for them to operate. We can generate an ecological proforma with this data. The farmhouse data is plotted in Fig. 9 showing somewhat typical environmental impact trends over time: if operating impacts are not within the site carrying capacity, there will continue to be a decline in available ecosystem services, with no possibility of recouping the initial construction impacts. The slopes of the lines show the trends as well as the path towards decreasing impacts.

Fig. 10 amends the diagram to produce a hypothetical regenerative project. To achieve this, the following design changes are made:

(1) Operating impacts are reduced to be within site capacity (IBS = 0.9);
(2) The energy productivity of the building is increased, and the land productivity by increased by 50% in year 5.

With these performance improvements, an upward trend is seen in the ecological balance with a net ecological profit occurring after about 20 years. After this, the construction investment of global ecological capital is paid off with increased ecoservices available henceforth. From this exercise, effective means for designing to meet sustainability can be summarized as follows:

(1) Increase the building efficiency (reduced size and reduced construction and operating impacts);
(2) Increase the ecological productivity (increase site size, and increase the building and site productivity).

5. Farmhouse strategies for reducing building impacts

5.1. Concept

In the farmhouse, a developing environmental building typology is demonstrated that reduces a

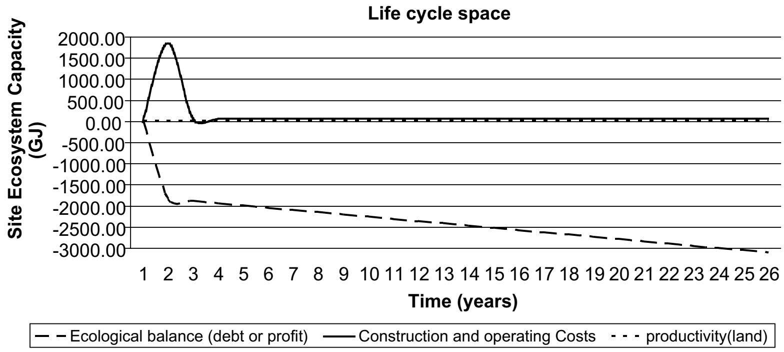

Fig. 9. The ecological proforma for the farmhouse.

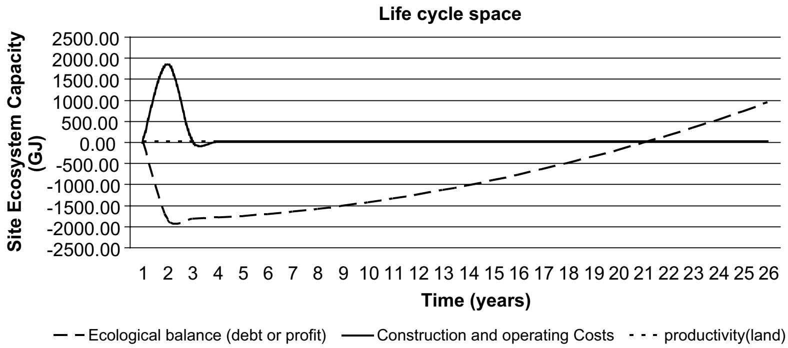

Fig. 10. The ecological proforma for a hypothetical regenerative project: reduced operating costs to within site capacity, increased building energy productivity, and increase land productivity by 50% in year 5.

building's ecological footprint through energy savings strategies in both the construction and operational phases. The farmhouse is based on utilization of society's waste streams as sources for building materials and construction methods. It is an architecture of assimilation and filtering. Since society relies on ecosystems to filter, detoxify, decompose, and encapsulate waste materials, the farmhouse offers opportunities to relieve a percentage of this burden placed on nature and reduce a building's ecological footprint by redirecting these materials into useful, low-embodied energy products.

The major materials used in the farmhouse have low overall embodied energy, offering rapid construction methods, cost-effectiveness, possibilities for new architectural aesthetics, and reduced ecological footprints. They are typically bio-based, low-to-no-toxin, energy-efficient, recycled content and/or reused. The following shows a few examples of how material selection in the farmhouse reduces construction and ecological impacts.

5.2. Bio-based materials

Bio-based building materials are produced from plant fiber waste such as soy, jute, kenaf, wheat, flax, corn, sunflowers, hemp, bamboo, wood, and paper waste. By their very nature, these rapidly renewable materials generate low embodied energy products. These are non-food, non-feed resources, which are factory pressed and molded into panels, bricks and other building products. Bio-based building materials replace petroleum-based building counterparts throughout the farmhouse. For example, the farmhouse used these materials for components such as interior walls, flooring, movable partitions, window coverings, cabinets, furniture, shelving, finishes, some structural insulated panels, and other assemblies. Gridcore-engineered molded fiber panels, co-developed by one of the authors, are lightweight, structural wallboards from 100% recycled paper and water. Gridcore panels require fewer framing members than standard wood and sheetrock assemblies and are used in the farmhouse as a replacement to gypsum products for walls and ceilings. Gridcore is produced from 100% waste paper and waste wood. It can be used for interior walls and ceilings and reduces by 50% the amount of lumber used in this type of standard framing system (Fig. 11).

5.3. Energy efficient materials

Energy-efficient materials used in the farmhouse result in reduced energy consumption during construction

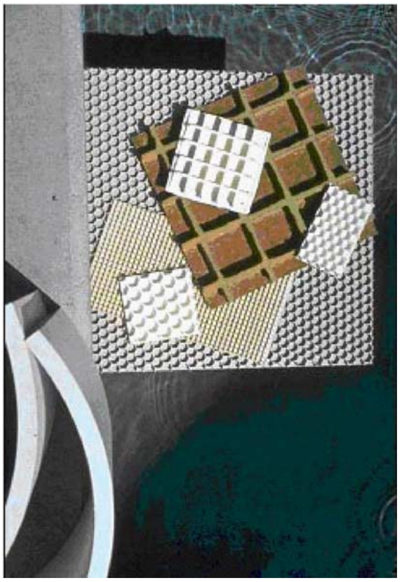

Fig. 11. A selection of gridcore products used in the farmhouse as walls, ceilings, and furniture and as a replacement to sheet-rock.

as well as through the building's life cycle operation. Several of these materials are structural insulated panels, known as SIPs, non-CFC styrofoam insulation, and engineered lumber from wood fibers, strands, and chips. In the farmhouse, exterior enclosing walls and roof are built from highly insulative SIPs. These lightweight sandwich panels are factory-produced, shaped, and shipped to building sites for rapid assembly that results in reduced labor and energy use in the construction

Fig. 12. The farmhouse exterior wall system, north elevation showing structural insulated panels with natural stucco.

Fig. 13. The farmhouse interior with 100-year-old salvaged wood columns and engineered wood beams. The interior of the house is comprised of biobased, recycled, and reused materials as well as engineered lumber and low-to-no-toxin finishes. All furniture is salvaged, reclaimed, and renewed.

Table 4
Embodied energy required for bio-based gridcore panels on reused lumber compared to standard wood frame and gypsum wall partitions

Bio-based gridcore interior partition wall with 2″ × 4″ × 10′ salvaged wood studs, 2 ft on center and 5/8″ gridcore both sides	2.7 MJ/kg
Standard 2″ × 4″ × 10′ wood studs, 16″ on center with 1/2″ gypsum board each side	4.35 MJ/kg
Net EE savings	1.65 MJ/kg

Table 5
Embodied energy required for energy-efficient wheat straw SIPS compared to standard wood frame, sheathing, and fiberglass insulation exterior walls

Energy efficient wheat straw structural insulted panel with natural stucco exterior finish and plaster interior finish	4.6 MJ/kg
Standard wood frame exterior wall with wood siding, building paper, plywood, 2″ × 4″ × 10′s at 16″ on center, gypsum interior wall board, 3.5″ batt insulation	6.8 MJ/kg
Net EE savings	2.2 MJ/kg

Table 6
Embodied energy required for reused structural wood members compared to standard structural steel members

Salvaged Douglas fir columns, $14'' \times 14'' \times 1'$ section (gasoline for delivery only)	0.2 MJ/kg
Standard structural steel tube, $4'' \times 4'' \times 3/16''$	32 MJ/kg
Net EE savings	31.8 MJ/kg

process. The high insulative value of SIPs results in lowered year-round energy use for building operation (Figs. 12 and 13 and Tables 4 and 5).

5.4. Reused materials

Reused or "experienced" materials are used throughout the farmhouse mainly in the form of construction demolition waste. A deteriorated existing residence at the farmhouse site was de-constructed with many materials, especially wood framing recycled back into the new farmhouse. Re-used materials in the farmhouse range from structural members, recycled lumber, framing members, doors, furniture and lighting to plumbing fixtures. In the farmhouse, 100-year-old salvaged ponderosa pine and Douglas fir columns were used as the main structural frame of the building. The home's main handrail is constructed from structural aluminum diverted from the landfill and abandoned wooden communication spools disassembled to yield stair balusters (Table 6).

6. Conclusion

Assessing the environmental impacts of buildings is inherently an interdisciplinary issue. The concept of ecological capacity extends into an architectural context, and is developed as a time and area dependent tool to evaluate the effectiveness of environmental building design. By basing the measure of building impacts on the ecological capacity of a site, we find a common language between architectural and ecological disciplines as well as generate useful analyses for establishing sustainability parameters. This method offers the additional benefit of generating environmental design criteria that can reduce the environmental impacts of construction, as shown in the farmhouse evaluation.

The use of ecosystems services criteria is a simple and effective method for objectively assessing the ecological impacts of a building. The overall size of the impact is measurable (IBS), as well as the ecological efficiency of the building (IES). The common baseline (hectare/years) allows projects of different sizes and typologies to be rationally compared. In application, this method allows building designers to plan the ecological debit and return of their interventions, much as they may develop a financial plan. The method recognizes individual efforts towards environmental responsibility, and also shows the magnitude of our interdependence. An ecologically derived baseline is shown to measure negative impacts as well as positive impacts of buildings. As we increase the positive impacts of our buildings beyond their negative impacts, we will have a net positive change on our ecosystems structure. This is a profound change in thinking, making us into guardians of our environment, where we are continually investing in and profiting from our environmental stewardship. The implication of this information is that as the value of our ecosystem services become socially recognized, it will be well within our technical means to design buildings to create an ecological profit.

References

American Institute of Architects, 1997. AIA Environmental Resource Guide. John Wiley and Sons Inc.

Baldwin, R., Yates, A., Howard, N., Rao, S., 1998. BREEAM 98 for Offices. Building Research Establishment, Watfordt.

Costanza, R., d'Arge, R., de Groot, R., Faber, S., Grasso, M., Hannon, B., et al., 1997. The value of the world's ecosystem services and natural capital. J. Nature 387, 253–260.

Knapp, K., 2000. An Empirical Perspective on the Energy Payback Time for Photovoltaic Modules. ASES 2000 Conference Proceedings.

Milne, G., Reardon, C., 2003. Embodied Energy. CSIRO Maunfacturing and Infrastructure technology environment. online brochure http://www.cmit.csiro.au/brochures/tech/embodied/index.cfm.

Stein, R.G., 1981. Handbook of Energy Use for Building Construction. USDOE/CE1220220-1, March 1981.

Wackernagle, M., Rees, W., 1996. Our Ecological Footprint. New Society Publishers.

Wilson, E.O., 1992. The Diversity of Life. W. Norton and Company. p. 347.