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LANDSCAPE DEVELOPMENT INTENSITY INDEX

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Abstract. The condition of landscapes and the ecological communities within them is strongly related to levels of human activity. Human-dominated land uses and especially the intensity of the uses can affect adjacent ecological communities through direct, secondary, and cumulative impacts.Using land use data and a development-intensity measure derived from energy use per unit area, an index of Landscape Development Intensity (LDI) can be calculated for watersheds of varying sizes to estimate the potential impacts from human-dominated activities that are experienced by ecological systems within those watersheds. The intended use of the LDI is as an index of the human disturbance gradient (the level of human induced impacts on the biological, chemical, and physical processes of surrounding lands or waters). The LDI can be used at the scale of river, stream, or lake watersheds or at the smaller scale of individual isolated wetland watersheds. Based on land uses and land cover, the LDI can be applied using available GIS land use/land cover data, aerial photographs, or field surveys.A description of data needs and methods for calculating an LDI index and several applications of the index as a land use based ranking scheme of the human disturbance gradient for watersheds are given.

Keywords: disturbance gradient, emergy, landscape development intensity

1. Introduction

The intensity of human dominated land uses in a landscape affects ecological processes of natural communities. The more intense the activity, the greater the effect on ecological processes. Consider for instance, the two extremes of full development on the one hand and completely natural on the other. A fully developed landscape, dominated by high-energy land uses, may have few, if any functional, natural ecological systems. At the other extreme, a natural landscape, one with no agricultural or urban development, would probably have intact ecological systems and processes. Landscapes in most regions of the globe fall somewhere between these two extremes in a gradient extending from completely natural to highly developed. They are composed of some developed areas but also have some natural ecological communities. The intensity of human uses may be a suitable metric for the disturbance gradient that results from increasing human use of landscapes.

Most landscapes are composed of patches of developed land and patches of wildlands,[1] or undeveloped lands that remain within a developed landscape mosaic. Although not directly converted, often wildlands experience cumulative secondary impacts that originate in developed areas and that spread outward into surrounding

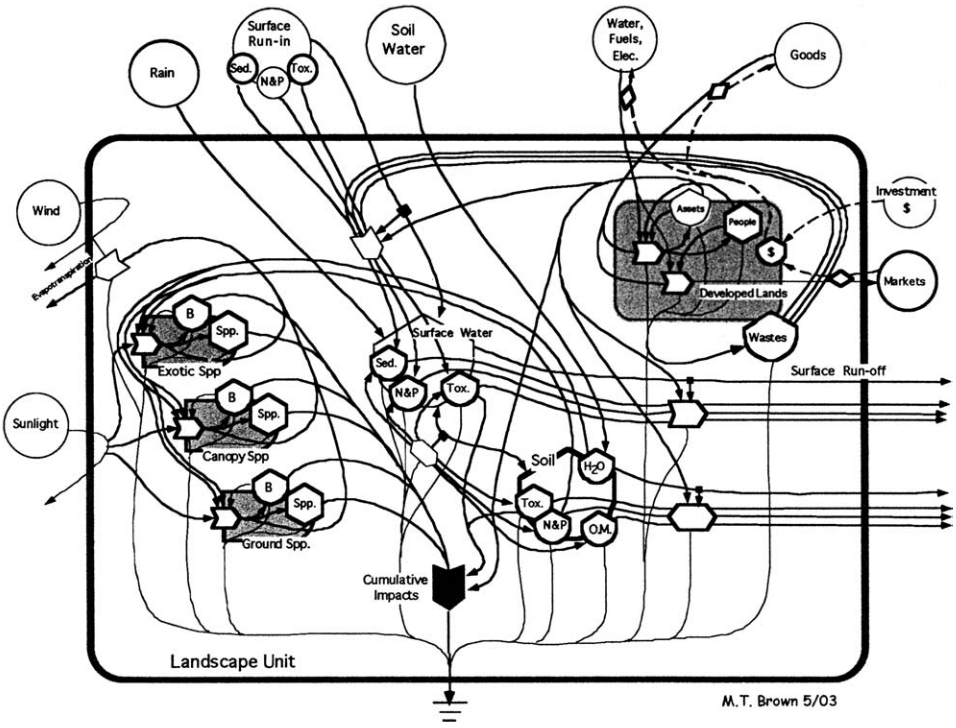

Figure 1. Systems diagram showing the effects of developed lands on wildlands. The more intense the development, the larger the effects. B = biomass, Spp = species, Sed = sediments, N & P = nitrogen and phosphorus, Tox. = toxins, O.M. = organic matter.

and adjacent undeveloped lands. The more developed a landscape, the greater the intensity of impacts. The systems diagram in Figure 1 illustrates some of the impacts originating in developed lands that are experienced by surrounding and adjacent wildlands. They come in the form of air- and water-born pollutants, physical damage, changes in the suite of environmental conditions (like changes in groundwater levels or increased flooding), or combinations of all of them. Pathways from the developed lands module on the right carry nutrients and toxins that affect surface and ground water which in turn negatively affect terrestrial, marine and aquatic systems. Other pathways interact directly with the biomass and species of wildlands, decreasing viability and quantity of each. Pathways that affect the inflow and outflow of surface and groundwater may alter hydrologic conditions, which in turn, may negatively affect ecological systems.

In summary, much attention has been given recently to the relationships between land use and the quality of ecological communities (see for example; Allan *et al.,* 1997; Beaulac and Reckhow, 1982; Crosbie and Chow-Fraser, 1999; Ehrenfeld, 1983; Galatowitsch *et al.*, 2000; Kirkman *et al.*, 1996; Richards *et al.*, 1996; Roth *et al.,* 1996), the development of classification systems for watersheds (Habersack, 2000; Hawkins, *et al.,* 2000; Hawkins and Vinson, 2000), biological indicators of ecosystem health (Jones *et al.*,2001; Patil, 2001), and indices of biological integrity for streams (Barbour *et al.*, 1996; Karr and Chu, 2000; Gerritsen and White,1997). These efforts assume that human activities, which are tied to land uses, have effects on ecological functions, health, or integrity, yet there is a paucity of studies in the literature that have quantitatively evaluated the human disturbance gradient . Development of classification systems, indicators and indices require the measurement of the human disturbance gradient or an index of the intensity of impacts from human dominated activities. In this study, we develop a method of quantitatively evaluating the human disturbance gradient that is applicable to landscapes of varying scales from watersheds to forest patches or isolated wetlands.

2. Methods

The LDI is a land use based index of potential human disturbance. It is calculated spatially based on coefficients applied to land uses within watersheds. These methods are based on the use of a Geographic Information System (GIS) and compatible land cover/land use digital data, although the same analysis can be accomplished by hand using aerial photographs. While the analysis can be carried out by hand, GIS will be essential for large watersheds or a regional effort to characterize disturbance gradients for many ecological communities.

2.1. DELINEATION OF AREA OF INFLUENCE

Land uses in the area "contributing" to a landscape unit[2] are first characterized and then an intensity factor assigned to each land use type. Development intensity factors are a function of the energy use per unit area of land use. A total area weighted development intensity is calculated for the area of influence.

The area of influence or extent of landscape that needs to be delineated depends on the type of landscape unit that is the subject of the evaluation. The area should include all lands that "contribute" to the landscape unit. In most cases, the watershed or drainage basin of the landscape unit is the most easily delineated. For large scale units such as rivers, streams, or lakes, delineated coverages of drainage basins often exist as part of GIS databases kept by various agencies of local, state, and federal government. For an individual wetland or forest patch, the area of influence is the surrounding landscape and could be delineated as the watershed of the ecosystem if topographic coverages are available. Experience in Florida's relatively flat terrain has shown however, that a characterization of the lands within a 100 m buffer around an isolated wetland or forest patch is sufficient to "capture" the disturbance gradient (Lane, 2003). As a result of the present investigation, we found that in the absence of any particular landscape feature such as a drainage structure that may direct stormwater into a wetland or water body, a 100 m buffer was adequate to capture surrounding land use effects.

2.2. CHARACTERIZATION OF LAND USES

The use of existing land use/land cover GIS data from recent spatial data bases will save considerable time. If these data are not available, land uses can be delineated on aerial photographs. When existing GIS land use/ land cover data are used, it is important to update and verify land uses in the area of influence through ground truthing or verification using recent aerial photographs. Digital Orthophoto Quads (DOQ) have been used to good effect for ground truthing land use/land cover data from other sources. Newly obtained DOQs are available for many parts of the country.

Land use/land cover classification schemes vary from region to region, and obviously in detail depending on scale of analysis. In Florida, the most used classification scheme is the Florida Land Use and Cover Classification System (FLUCCS), a hierarchical system of classification that begins with three broad classes: urban, agriculture, and natural (FDOT, 1999). The classification system further subdivides each main class into finer and finer detail with each level of increasing resolution. Table I lists the classification scheme adopted for the LDI analysis. It is based on the FLUCCS categories, but differs slightly. The main concern was to keep the classes defined as closely to original classes used in developing the energy flow characteristics of land use types as possible, and to make visual interpretation from aerial photographs relatively straight forward.

2.3. QUANTIFYING HUMAN-DEVELOPMENT INTENSITY BY LAND USE

The metric used for quantifying human activity is emergy[3] use per unit area per time. Emergy is energy that has been corrected for different qualities, and its unit of measure is the solar emergy joule (abbreviated sej). Thus the units for quantifying the intensity of human activity are sej/ha yr^{-1}. Emergies used in calculating the LDI are all nonrenewable energies including electricity, fuels, fertilizers, pesticides, and water (both public water supply and irrigation).

Referred to as "empower density," emergy use per area per time is calculated as average values for land use categories from previous studies (Brown, 1980; Whitfield, 1994; Brandt-Williams, 2002). In these previous studies, energy consumption data were collected from actual billing records and from the literature and averaged on a per unit area basis for different land use types. Since the LDI is a measure of human activity, only nonrenewable energies and related services are used in the calculation. Included as Appendix B are two tables that give details of the evaluation of land uses: (i) an evaluation of citrus agriculture and (ii) an evaluation of low-density single family residential (1.5 units per hectare).Table II summarizes the nonrenewable empower densities of the various land uses in the second column.

The last column in Table II is the LDI coefficient for each land use type. The LDI coefficient is calculated as the normalized natural log of the empower densities.

TABLE I
Land uses and definitions

Land use/land cover	Definition
Natural land/open water	Open water, upland, or wetland with very low manipulations (i.e. state parks, refuges, preserves and other protected lands).
Tree plantations	Land devoted to silviculture with varying stocking densities.
Unimproved pastureland	Native rangeland and woodland pasture with presence of livestock.
Improved pasture (no livestock)	Areas where the natural vegetation has been altered by drainage, irrigation, etc., for the grazing of domestic animals. Does not include livestock.
Improved pasture–low-intensity (with livestock)	Areas where the natural vegetation has been altered by drainage, irrigation, etc., for the grazing of domestic animals with a density of less than 1.2 animals/ha.
Improved pasture–high-intensity (with livestock)	Areas where the natural vegetation has been altered by drainage, irrigation, etc., for the grazing of domestic animals with a density of more than 1.2 animals/ha.
Citrus	Areas devoted to the production of oranges and citrus in general.
Row crops	Areas devoted to the production of all types of vegetables usually grown in rows, whether producing or not.
General agriculture	Applies to type of crop not known or crops other than citrus or row crops.
Agriculture–high-intensity	Dairy farms and large-scale cattle feed lots, chicken farms, and hog farms.
Recreational/open land–low-intensity	Areas of natural vegetation in cities maintained as nature parks, and undeveloped land that may be occupied by natural vegetation in an agricultural or urban landscape. Also includes access roads within conservation/protected lands.
Recreational/open space–medium-intensity	Areas with grassy lawns in urban landscape including recreational land such as playgrounds, ball fields, and swimming beaches. Also applies to land that has been cleared and prepared for construction, dirt roads, barren land, and open areas surrounding power lines. Includes human-created water bodies (retention ponds, canals, reservoirs, etc).
Recreational/open land–high-intensity	Applies to stadiums not associated with institutions such as schools and universities, golf courses, and racetracks (horse, dog, car).
Single family residential–low-density	Areas that are predominantly residential units with a density less than 10 units/ha.
Single family residential–medium-density	Areas that are predominantly residential units with a density between 10 and 20 units/ha.
Single family residential–high-density	Areas that are predominantly residential units with a density of more than 20 units/ha.
Multi-family residential–low-intensity	Areas that are predominantly multi-family residential units such as condominiums and apartment buildings up to 2 stories.

(*Continued on next page*)

TABLE I

(*Continued*)

Land use / land cover	Definition
Multi-family residential–high-intensity	Areas that are predominantly multi-family residential units such as condominiums and apartment buildings with 3 or more stories.
Commercial–low-intensity	Commercial strip.
Commercial–high-intensity	Commercial mall with associated storage buildings and parking lots, hotels, convention centers, and theme parks.
Institutional	Schools, universities, religious, military, medical and professional facilities, and government buildings.
Industrial	Land uses include manufacturing, assembly or processing of materials/products and associated buildings and grounds. Also includes extractive areas and mining operations, water supply plants, waste treatment facilities, and solid wastes disposal facilities.
Transportation–low-intensity	Paved road with 2 lanes (includes shoulders), railroads, and canals used for transportation.
Transportation–high-intensity	Paved road with more than 2 lanes (includes shoulders), airports, railroad terminals, bus and truck terminals, port facilities, and auto parking facilities when not directly related to other land use.
Central business district–low-intensity	Central business districts with an average of 2 stories.
Central business district–high-intensity	Central business districts with an average of more than 2 stories.

First the natural log of the empower densities were calculated and then the resulting values were normalized on a scale from 1 to 10, with the LDI coefficient for natural lands equal to 1.0 and a LDI coefficient of 10.0 for the highest intensity land use, the Central Business District.

2.4. CALCULATING AN AREA-WEIGHTED LDI

Land uses within the “area of influence” are assigned an LDI coefficient from Table II, and then an overall LDI ranking is calculated as an area weighted average. Using the GIS, total area and percent of total area occupied by each of the land uses is determined and then the LDI calculated as follows:

$$\mathrm{LDI}_{\mathrm{total}} = \sum \%\mathrm{LU}_{\mathrm{i}} \cdot \mathrm{LDI}_{\mathrm{i}} \tag{1}$$

where

$\mathrm{LDI}_{\mathrm{total}}$ = LDI ranking for landscape unit

$\%\mathrm{LU}_{\mathrm{i}}$ = percent of the total area of influence in land use i

$\mathrm{LDI}_{\mathrm{i}}$ = landscape development intensity coefficient for land use i

TABLE II

Land use classification, nonrenewable empower density, and resulting LDI coefficients

Land use	Nonrenewable empower density (E14 sej/ha/yr)	Ln Nonrenewable empower density	LDI coefficients[a]
Natural system	0.00		1.00
Natural open water	0.00		1.00
Pine plantation	5.10	1.63	1.58
Recreational / open space – low-intensity	6.55	1.88	1.83
Woodland pasture (with livestock)	8.00	2.08	2.02
Improved pasture (without livestock)	17.20	2.84	2.77
Improved pasture – low-intensity (with livestock)	33.31	3.51	3.41
Citrus	44.00	3.78	3.68
Improved pasture – high-intensity (with livestock)	46.74	3.84	3.74
Row crops	107.13	4.67	4.54
Single family residential – low-density	1077.00	6.98	6.9
Recreational / open space – high-intensity	1230.00	7.11	6.92
Agriculture – high intensity	1349.20	7.21	7.00
Single family residential – medium density)	2175.00	7.68	7.47
Single family residential – high density	2371.80	7.77	7.55
Mobile home (medium density)	2748.00	7.92	7.70
Highway (2 lane)	3080.00	8.03	7.81
Low-intensity commercial	3758.00	8.23	8.00
Institutional	4042.20	8.30	8.07
Highway (4 lane)	5020.00	8.52	8.28
Mobile home (high density)	5087.00	8.53	8.29
Industrial	5210.60	8.56	8.32
Multi-family residential (low rise)	7391.50	8.91	8.66
High-intensity commercial	12 661.00	9.45	9.18
Multi-family residential (high rise)	12 825.00	9.46	9.19
Central business district (average 2 stories)	16 150.30	9.69	9.42
Central business district (average 4 stories)	29 401.30	10.29	10.00

[a] The LDI coefficient is calculated as the normalized (on a scale of 1.0 to 10.0) natural log of the empower densities.

3. Results

Several aspects of calculating LDIs are given next. First the effect of the area of influence on LDI "scores" for isolated wetlands in Florida is discussed, and then two case studies are presented as examples of the use of LDI at a watershed scale and at the scale of individual isolated depressional wetlands.

3.1. APPROPRIATE AREA OF INFLUENCE

We have tested various methods for calculating LDIs for the watershed of wetlands, including distance weighting, and several different areas of influence around wetlands. Calculating LDIs within increasing buffers surrounding wetlands tested the effect of the area of influence.Figure 2 shows the results of LDI calculations for buffers of 100 and 200 m for a set of 49 wetlands in Central Florida. There was no significant difference ($t_{(48)} = 0.44$, $p = 0.66$) between LDIs calculated using the 100 m area of influence and the 200 m area(Wilcoxon Signed Rank Test for differences, $p = 0.726$). We extended the buffer distance to as much as 500 m,and while there were differences in the mean LDIs calculated for each buffer distance, their power as a predictor of WRAP score (see below) declined.

The effect of distance weighting on LDI was tested using the 100 m buffer distance for a sample of 36 wetlands from Central and South Florida. First the LDI was calculated, giving equal weight to the land use within the buffer regardless of the distance from the wetland. Then the LDI was calculated, assuming that the effect of development intensity on the landscape unit decreases linearly with distance.Figure 3 shows the results of comparison of the two methods. Essentially, there was no significant difference between the equal distance LDI (LDI-SAW) and the distance weighted LDI (LDI-DW).

In summary, it was found that a 100 m area was sufficient to “capture” effects and that a distance-weighted method was no better than a simple area-weighted calculation. Since the amount of time required to calculate the distance-weighted LDI is significantly more than the area-weighted LDI, distance weighting was considered not to be cost effective.

4. Case Studies Using LDI

Presented next are two applications of LDI at different scales of analysis. In the first, LDI rankings were calculated at the watershed scale and related to total phosphorus loading. In the second application, LDI was related to a wetland assessment procedure developed in South Florida (Wetland Rapid Assessment Procedure or WRAP; [Miller and Gonsalus, 1997]), which was calculated for depressional herbaceous wetlands.

4.1. WATERSHED SCALE APPLICATION OF LDI

Parker (in Brown *et al.*, 1998) calculated several different LDIs for 64 watersheds in the St. Marks River basin of the Florida Panhandle and related them to total phosphorus loading. Phosphorus loading was calculated using event mean concentration data within a GIS spatial model. The watersheds represented varying degrees of development. Several of the watersheds were highly urbanized, containing the

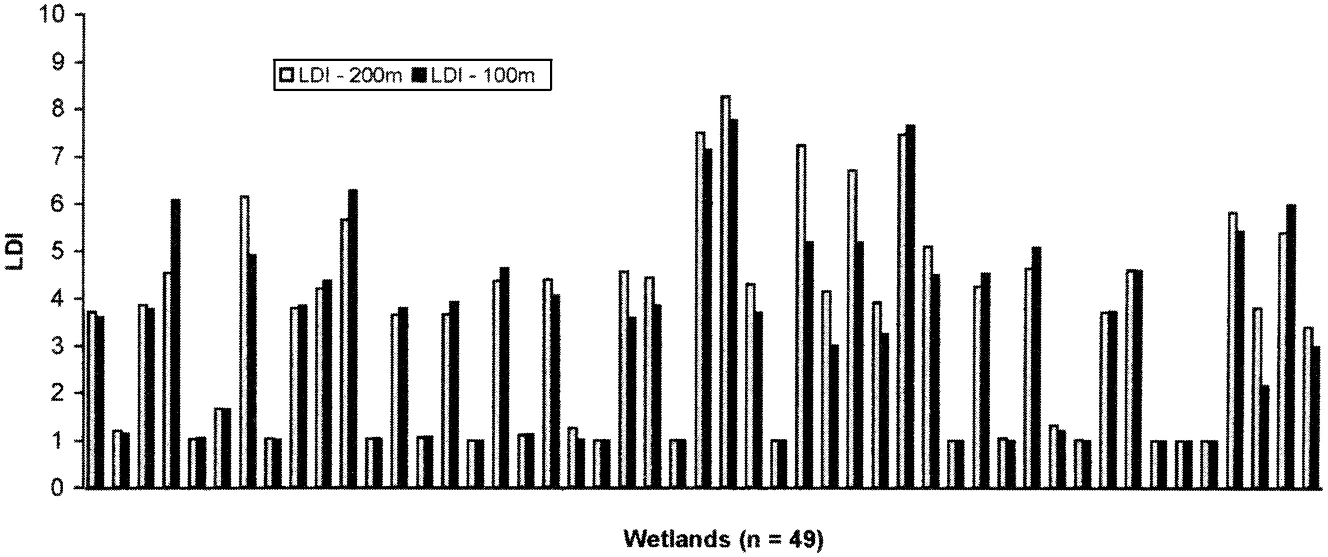

Figure 2. Graph of calculated LDIs for 49 wetlands in Central Florida, showing no significant differences between LDIs calculated using 100 and 200 m buffer.

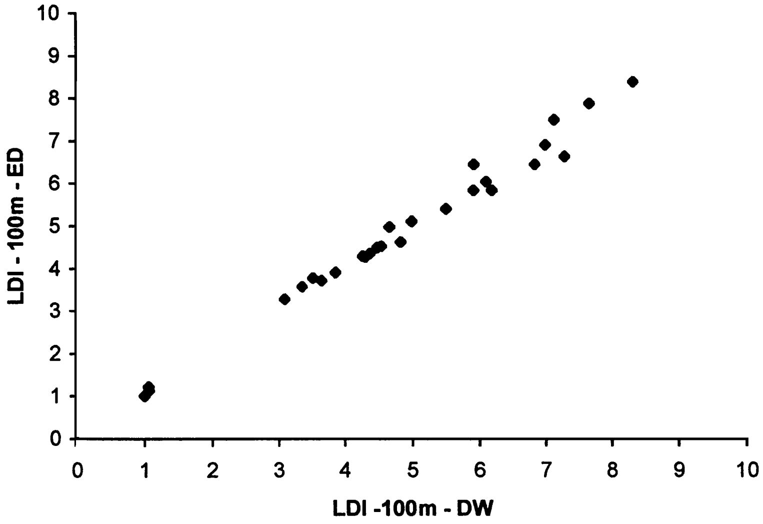

Figure 3. Graph of distance-weighted LDI (LDI-100 m-DW) plotted against a simple area-weighted LDI (LDI-100 m-SAW) for 36 wetlands in central Florida showing no significant difference between the two methods of calculating the index.

high intensity core commercial and institutional uses of city of Tallahassee, Florida (LDIs of greater than 8.0) as well as suburbs of the city dominated by single-family residential development (LDIs of 6.0 to 8.0). Agricultural uses in the watersheds were primarily row crops and pasture. (LDIs values between 2.0 and 5.0). Watersheds with minor agricultural or urban land uses were rare (LDIs less than 2.0).

The graph in Figure 4 uses Parker's data, but recalculates LDI using Equation 1. LDI values of 1.0–2.0 correspond to watersheds that are nearly 100% natural lands; watersheds with LDI values between 2.0 and 5.0 are primarily agricultural while those greater than 5.0 are dominated by urban land uses. The variability in background concentrations of P evident in watersheds having low LDI scores (less than 3.0) is the result of subtle differences in relatively small development patterns of farms and rural roads in undeveloped watersheds. With increasing area and intensity of development, the modeled pollutant loads are highly correlated with the LDI values ($r^2 = 0.877$, $p = 0.05$).

4.2. LDI APPLIED TO DEPRESSIONAL HERBACEOUS WETLANDS

In recent studies of depressional wetlands in Florida, an LDI has been used to characterize the human disturbance gradient as a means of developing biological indicators for wetlands (Brown *et al.*, 2001, 2003; Lane, 2003). Currently, data on three assemblages, (macrophytes, macro-invertebrates, and algae) collected from over 250 herbaceous and forested depressional wetlands are being used to develop a Florida Wetland Condition Index (FWCI) for Florida wetlands.Figure 5 is a graph

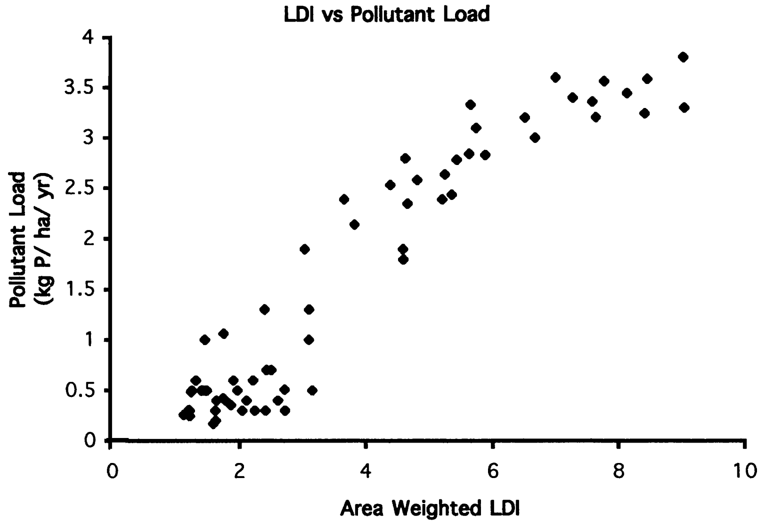

Figure 4. Area-weighted LDI versus phosphorus load in 64 hydrologic units (sub-watersheds) of the St. Marks River watershed.

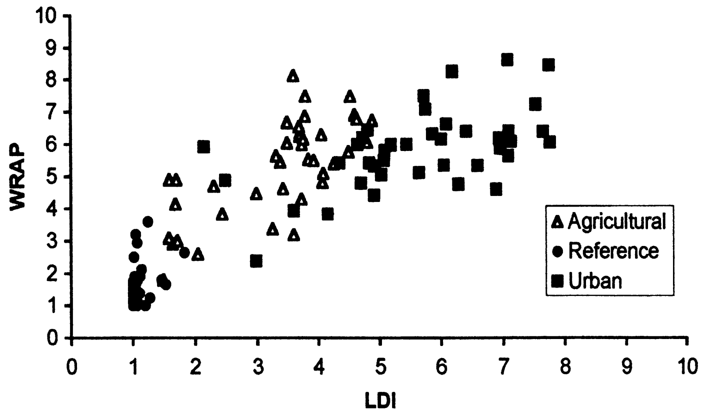

Figure 5. LDI versus Wetland Rapid Assessment Procedure Score. The WRAP score is generally on a scale of 0–3.0, with 3.0 as the best score. We have normalized the WRAP score to a scale of 1–10 (one being the best) for comparison with the LDI. Agricultural wetlands are embedded in primarily agricultural landscapes, urban wetlands are embedded in urban landscapes, and reference wetlands are embedded in landscapes with little or no agricultural or urban development.

of LDI versus the South Florida Water Management District's WRAP (Miller and Gonsalus, 1997) for 118 depressional forested wetlands in Florida. WRAP is a qualitative assessment of a wetland's functional capacity and is scored using six different variables: (i) wildlife utilization, (ii) wetland overstory/shrub canopy, (iii) wetland vegetative ground cover, (iv) adjacent upland support/wetland buffer, (v) field indicators of wetland hydrology, and (vi) water quality input and treatment systems.

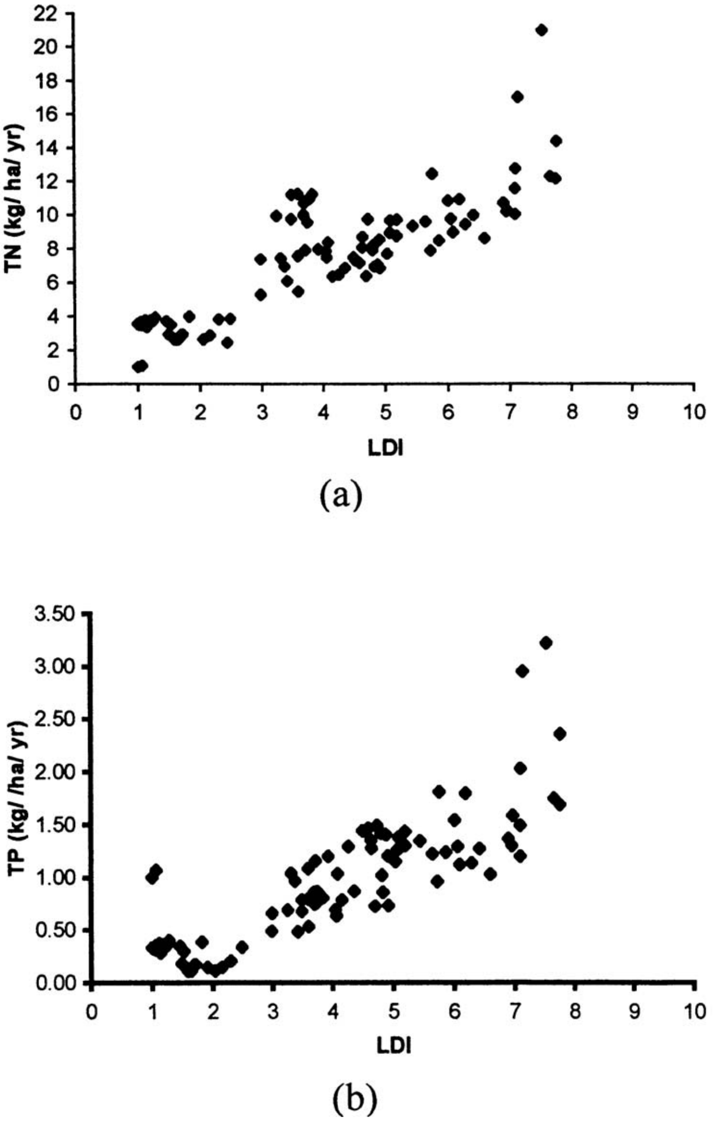

Figure 6. LDI versus modeled total nitrogen load (i) and total phosphorus load (ii) using 100 m buffer around 118 depressional wetlands in Florida.

LDI shows a relationship ($r^2 = 0.71$, $p = 0.05$) to the WRAP qualitative assessment scores. Analysis of the Florida data set, from which these data have been extracted, is continuing with development of biological indicators of wetland ecosystem health for both depressional marsh and forested wetlands.

Using a GIS pollutant loading model and land use data for depressional wetlands in the Florida data set, we evaluated pollutant loads from a 100 m buffer area surrounding each wetland. Figure 6 is a graph of modeled pollutant load

(TP and TN) for 118 depressional wetlands. The relationship between modeled pollutant load and LDI is similar to that found for sub-watersheds with increasing pollutant loads correlated to increasing LDI scores (TN: $r^2 = 0.75$ and TP: $r^2 = 0.74$; $p = 0.05$)

5. Conclusions

The LDI Index is a quantitative measure of the intensity of human use of landscapes. It is based on the use of energy per unit area converted to energy of one type (solar emergy). LDI differs from other measures of land use intensity because it scales the intensity of activity based on nonrenewable energy use, a characteristic common to all human dominated land uses. While it has been shown that percent impervious surface is a relatively good indicator of surface water pollution in watersheds, in agricultural watersheds where imperviousness may be relatively unimportant, the correlation between pollutant load and impervious surface declines. LDI, however, is a continuous index that ranks urban and agricultural land based on their nonrenewable empower density (emergy per unit area per unit time).

As a quantitative measure of the intensity of human use of landscapes, the LDI may be useful as a measure of the disturbance gradient in applications of bioindicator development. At this point in the development of the LDI, we believe that because of the small area of influence around isolated depressional wetlands, distance weighting may not be important (and our early tests of distance weighting appear to suggest this). However, as we apply the LDI concept to larger watersheds, distance may be a far more important variable. Some preliminary analysis of spatial pattern of development suggests aggregate measures of landscape pattern combined with distance may be important modifiers for LDIs at the watershed scale.

We believe that the LDI can be applied in other areas with minimal data acquisition and changes in the LDI Land Use/Land Cover coefficients. Since the LDI coefficients are normalized between the most intense and least intense land uses, it may be possible to apply the LDI coefficients calculated for Florida at other locations with minor adjustments.

Research on the LDI continues, using the empower of land uses and water quality data from numerous watersheds throughout Florida. Several different methods of accounting for spatial influences of human activities within the area of influence are being tested as well. The use of LDI as an index of human disturbance is being tested at three landscape scales: the scale of individual wetlands, the scale of sub-watersheds (HUC-6),[4] and at the larger scale of higher order basins (HUC-3) (Vivas, 2004). Spatial simulations of LDI have been evaluated as a means of determining buffer distances for set backs (buffer areas) between human dominated landscapes and sensitive wildlands (Brown, 2003).

Notes

1. For convenience the term wildlands is used inclusively to mean all natural ecological systems, both terrestrial and aquatic, as well as marine ecosystems. Wildlands are areas of the landscape that are not developed.
2. A landscape unit is the ecological community, drainage feature, or hydrologic system that is being studied. For instance, the study unit could be an individual ecological community such as a wetland, or a stream segment, or a sub-watershed drainage basin.
3. A more extended presentation of emergy, basic definitions, and concepts is given as Appendix A.
4. HUC stands for Hydrologic Unit Code. The United States is divided and sub-divided into successively smaller hydrologic units which, are classified into four levels: regions, sub-regions, accounting units, and cataloging units.

Appendix A: Brief Description of Emergy Definitions and Concepts

Emergy Accounting uses the thermodynamic basis of all forms of energy and materials, and converts them into equivalents of one form of energy, usually sunlight. Emergy is the amount of energy that is required to make something. It is the "memory of energy" that was degraded in a transformation process where energy of one form was transformed into energy of another form (for instance the transformation of sunlight into organic matter, or fossil fuels into electricity). The units of emergy are emjoules, to distinguish them from joules. Most often emergy of fuels, materials, services, etc., is expressed in solar emjoules (abbreviated sej). Emergy then, is a measure of the global processes required to produce something expressed in units of the same energy form. The more work done to produce something, i.e., the more energy transformed, the higher the emergy content of that which is produced.

To derive solar emergy of a resource or commodity, it is necessary to trace back through all the resources and energy that are used to produce it, and express each in the amount of solar energy that went into its production. This has been done for a wide variety of resources and commodities and the renewable energies driving the biogeochemical process of the earth (see Odum, 1996). When expressed as a ratio of the total emergy used to the energy of the product, a transformation coefficient results (called transformity whose dimensions are sej/J). As its name implies, the transformity can be used to "transform" a given energy into emergy, by multiplying the energy by the transformity. For convenience, in order not to have to calculate the emergy in resources and commodities every time a process is evaluated, previously calculated transformities are used.

DEFINITIONS

The following paragraphs contain definitions of emergy concepts. A more complete introduction can be found in H.T. Odum's text, *"Environmental Accounting: Emergy and Environmental Decision Making"* (Odum,1996).

Emergy is the availability of energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service. The unit of emergy is the *emjoule*, a unit referring to the available energy of one kind consumed in transformations. For example, sunlight, fuel, electricity, and human service can be put on a common basis by expressing them all in the emjoules of solar energy that is required to produce each. In this case the value is a unit of *solar emergy* expressed in *solar emjoules* (abbreviated sej).

Empower is a flow of emergy (i.e., emergy per time). Emergy flows are usually expressed in units of solar empower (solar emjoules per time).

Emjoule is the unit of measure of emergy, “emergy joule”. It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood.

Energy is sometimes referred to as the ability to do work. Energy is a property of all things, which can be turned into heat and is measured in heat units (BTUs, calories, or joules)

Nonrenewable Emergy is the emergy of energy and material storages like fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced by geologic processes.

Renewable Emergy is the emergy of energy flows of the biosphere that are more or less constant and reoccurring, and that ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.

Transformity is the ratio obtained by dividing the total emergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of emergy/energy (sej/J). A transformity for a product is calculated by summing all of the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different forms to emergy of the same form.

Appendix B

Example emergy evaluations of two land use subsystems: (i) One hectare of citrus grove, and (ii) one hectare of low density single family residential (1.5 units/hectare). The tables list annual emergy flows for the two subsystems that were used to calculate the empower densities in Table II. Only the nonrenewable emergies were summed to determine empower.

TABLE B-1
Emergy evaluation of oranges, per ha per year (after Brandt-Williams, 2002)

Note	Item	Data (units/yr)	Unit	Unit solar emergy (sej/unit)	solar emergy (E13 sej/yr)
Renewable inputs					
1	Sunlight	5.93E+13	J	1	6
2	Rain (chemical potential	6.25E+10	J	3.02E+04	189
3	Wind (kinetic energy)	2.36E+11	J	9.83E+02	23
Nonrenewable storages used					
4	Net Topsoil Loss	6.33E+08	J	1.24E+05	8
Purchased inputs					
5	Fuel	2.28E+07	J	1.11E+05	0.3
6	Electricity	4.68E+08	J	2.69E+05	13
7	Potash	2.36E+05	g K	1.85E+09	44
8	Lime	2.40E+05	g	1.68E+09	40
9	Pesticides	1.79E+04	g	2.52E+10	45
10	Phosphate	1.12E+04	g P	3.70E+10	42
11	Nitrogen	3.01E+04	g N	4.05E+10	122
12	Labor	3.79E+08	J	1.36E+05	5
13	Services	3.01E+02	$	4.03E+12	121
	Sum of nonrenewable & purchased inputs				440

Notes:

1 **Sunlight**

Annual energy = (Avg. Total annual insolation J/yr)(Area)(1-albedo)
Insolation = 6.90E+09 J/m^2/y (NCDC, 2000)
Area = 1.00E+04 m^2

2 **Rain**

Annual energy = (in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1-runoff)
Rain (in/yr) = 54 (NCDC, 2000)
Area (m^2) = 10000

Albido = 0.14 (Odum 1986)
Annual energy = 5.93E+13

Runoff coeff. = 7.70E-02 (AFSIRS estimate, Smajstrla, 1990)
Annual energy = 6.25E+10

3 **Wind kinetic energy**
Area = 1.00E+04 m^2
Density of Air = 1.30E+00 kg/m^3
Avg. annual wind velocity = 5.00E+00 mps (NCDC, 2000)
Geostrophic wind = 8.33E+00 mps
Drag Coeff. = 1.00E-03 (Miller, 1964 quoted by Kraus, 1972)
Energy (J) = (area)(air density)(drag coefficient)($velocity^3$)
= (____m^2)(1.3 kg/m^3)(1.00 E-3)(____mps)(3.14 E7 s/yr)
Energy(J) = 2.36E+11 J/yr

4 **Net topsoil loss**
Erosion rate = 70 g/m^2/yr (Pimentel *et al.*, 1995)
% organic in soil = 0.04 (Pimentel *et al.*, 1995)
Energy cont./g organic = 5.40 kcal/g
Net loss of topsoil = (farmed area)(erosion rate)
O. M. in topsoil used up = (total mass of topsoil)(% organic)
Energy loss = (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)
Annual energy = 6.33E+08

5 **Fuel** (includes diesel, gasoline, lubricants)
Annual energy = (gallons fuel) * (1.51E5 J/gal)
Gallons = 1.51E+02 FAECM data (Fluck *et al.*, 1992)
Annual energy = 2.28E+07

6 **Electricity, J**
Annual energy = KWh*3.6E6 J/KWh
KWh = 1.30E+02 FAECM data (Fluck *et al.*, 1992)
Annual energy = 4.68E+08

7 **Potash, g K per ha**
Annual consumption = (g fertilizer active ingredient)
(78 gmol K/94 gmol K2O)
g = 2.84E+05 FAECM data (Fluck *et al.*, 1992)
Annual consumption = 2.36E+05

8 **Lime, g per ha**
Annual consumption, g = 2.40E+05 FAECM data
(Fluck *et al.*, 1992)

9 **Pesticides, g per ha** (includes pesticides, fungicides, herbicides)
Annual consumption, g = 1.79E+04 FAECM data (Fluck *et al.*, 1992)

10 **Phosphate, g P per ha**
(g fertilizer active ingredient) (31 gmol P/132 gmol DAP)
g = 4.79E+04 FAECM data (Fluck *et al.*, 1992)
Annual consumption = 1.12E+04

11 **Nitrogen, g N per ha**
(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)
g = 1.42E+05 FAECM data (Fluck *et al.*, 1992)
Annual consumption = 3.01E+04

12 **Labor**
(pers-hr/ha/yr)*(3500 Cal/day)*(4186J/Cal)/(8 hr/day)
per-hour = 2.07E+02 FAECM data (Fluck *et al.*, 1992)
Annual energy = 3.79E+08

13 **Services, $ per ha**
$/yr = 3.01E+02 FAECM data (Fluck *et al.*, 1992)
Annual emergy = ($ /yr)(sej/$)

TABLE B-2

Emergy evaluation of single family residential land use (1 hectare)

	Note	Item	Data (units/yr)	Unit solar emergy (sej/unit)	Solar emergy (E13 sej/yr)	
Renewable inputs						
1	Sunlight	5.93E+13	J	1	6	
2	Rain (chemical potential)	2.71E+10	J	3.02E+04	82	
3	Wind (kinetic energy)	2.36E+11	J	9.83E+02	23	
Nonrenewable storages used						
4	Net topsoil loss	4.52E+07	J	1.24E+05	1	
Purchased inputs						
5	Natural gas	3.29E+10	J	1.11E+05	365	
6	Electricity	6.22E+09	J	2.69E+05	167	
7	Water	3.61E+09	gal	3.00E+05	108	
8	Food	4.19E+07	J	3.36E+06	14	
9	Goods	1.50E+04	$	1.10E+12	1650	
10	Pesticides	1.59E+04	g	2.52E+10	40	
11	Phosphate	8.44E+03	g P	3.70E+10	31	
12	Nitrogen	2.26E+04	g N	4.05E+10	91	
13	Construction materials	3.04E+07	g	1.55E+09	4712	(1.5 units/ha)
	Sum of nonrenewable and purchased inputs				7180	10770

Notes:

1 **Sunlight**

Annual energy = (Avg. Total annual insolation J/yr)(Area)(1-albedo)
Insolation = 6.90E+09 J/m^2/y (NCDC, 2000)

2 **Rain**

Annual energy = (in/yr)(Area)(0.0254 m/in)(1E6 g/m^3)
(4.94 J/g)(1-runoff)
Rain (in/yr) = 54 (NCDC, 2000)

Area = 1.00E+04 m^2
Albido = 0.14 (Odum 1987)
Annual energy = 5.93E+13

3 **Wind kinetic energy**
Area = 1.00E+04 m^2
Density of Air = 1.30E+00 kg/m^3
Avg. annual wind velocity = 5.00E+00 mps (NCDC, 2000)
Geostrophic wind = 8.33E+00 mps
Drag Coeff. = 1.00E-03 (Miller, 1964 quoted by Kraus, 1972)
Energy (J) = (area)(air density)(drag coefficient)(velocity^3)
= (____m^2)(1.3 kg/m^3)(1.00 E-3)(____mps)(3.14 E7 s/yr)
Energy(J) = 2.36E+11 J/yr

5 **Natural gas**
Annual energy = (therms) * (1.055 E8 J/therm)
Therms = 3.12E+02 (Gainesville Regional Utilities, 2002)
Annual energy = 3.29E+10

7 **Water**
Annual consumption = (gallons)(3785 cm3)(1 g/cm3)(4.94J/g)
gal = 1.93E+05 (Gainesville Regional Utilities, 2002)
Annual consumption = 3.61E+09

9 **Goods**
Annual Consumption = $15000

11 **Phosphate, g P per ha**
(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)
g = 3.59E+04 estimate
Annual consumption = 8.44E+03

13 **Construction materials**
mass (g) = (total weight)/(50 yrs)
Total weight = 1.52E+09 (Haukoos, 1994)
mass (g) = 3.04E+07

Area (m2) = 10000
Runoff coeff. = 6.00E-01 estimate
Annual energy = 2.71E+10

4 **Net topsoil loss**
Erosion rate = 5 $g/m^2/yr$ (Pimentel *et al.*, 1995)
% organic in soil = 0.04 estimate
Energy cont./g organic = 5.40 kcal/g
Net loss of topsoil = (farmed area) (erosion rate)
O. M. in topsoil used up = (total mass of topsoil) (% organic)
Energy loss = (loss of organic matter) (5.4 kcal/g) (4186 J/kcal)
Annual energy = 4.52E+07

6 **Electricity, J**
Annual energy = KWh*3.6E6 J/KWh
KWh = 1.73E+03 (Gainesville Regional Utilities, 2002)
Annual energy = 6.22E+09

8 **Food**
Annual consumption = (2500 Cal/day)(4187 J/Cal)
(4 per/household)
Annual consumption, g = 4.19E+07

10 **Pesticides, g per ha** (includes pesticides, fungicides, herbicides)
Annual consumption, g = 1.59E+04 estimate

12 **Nitrogen, g N per ha**
(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)
g = 1.07E+05 estimate
Annual consumption = 2.26E+04

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