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ANALYSIS

# Resource-based sustainability indicators: Chase County, Kansas, as example

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**Abstract**

We develop three quantitative indicators of the physical/biological aspect of sustainability. They are based on depletion of resources, dependence on outside subsidies, and disruption of natural cycles. We apply the indicators to an agricultural county in Kansas, using energy, water, soil, and nitrogen as numeraires. 9/10 of Chase County is dedicated to range beef cattle grazing and 1/10 to row-cropping and confinement animal feeding. Range production is relatively non-depleting, independent, and non-disrupting. Cropping is more depleting, dependent, and disrupting, but comparable with that in other agricultural areas. We discuss how this pattern, mediated by absentee land-holding and low human population density, trades off against economic income. With the exception of energy, all analyses are only in terms of direct flows (e.g. actual amounts crossing the county boundary). For energy, we also estimate the energy consumed elsewhere to produce imported non-energy goods and services. © 2002 Elsevier Science B.V. All rights reserved.

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## 1. Introduction: general concerns about sustainability indicators

Sustainablity has ecological, economic, and social components (Goodland and Daly, 1996). Initially the emphasis was strongly on ecology, but recently the pendulum has swung to the other side, sometimes stressing economic and social issues to the neglect of biophysical (ecological) considerations. As resource analysts with backgrounds in physical science and engineering, we are tempted to be critical of sustainability plans which pay little or no attention to energy, water, etc., impacts, especially off-site. For example, this lack is typified by The Community Indicators Handbook (Redefining Progress, 1997), which otherwise is generally useful and comprehensive. At the same time, we acknowledge the potential dissonance between the analyst's overview and practitioner's practical difficulties. Even the relatively new field of ecological economics has a strong internal discussion on the degree to which

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biophysical issues should be a routine aspect of all sustainability work (EE Forum, 1999).

In the long term, depletion of lifestyle-support is the fundamental sustainability issue, and the demands and impacts of the human endeavor relative to the capacity of the global system the major question. However, we are not at long term; we are at the intermediate state identified by Daly (1996) as between spaceship (tight resource limits) and frontier (no limits). Therefore, two other issues besides depletion require attention–dependence of one region upon another, and disturbance of natural flows.

In the long term we may not need to treat dependence because the entire globe could (institutionally) act as one system and there would be no smaller subsystems which could subsidize or parasitize others. In the transition to a more global view and system, however, knowing interdependence of smaller units (countries, regions, states, counties) is important. Without assessing dependence, we allow intentional or inadvertent ignoring of imperfectly priced subsidies and impacts both up- and down-stream. Defining sustainability requires setting a time horizon for maintaining capabilities of ecological, economic, and social systems, but we still need transitional indicators to gauge progress and to anticipate the following problems:

1. geographically discounting consciously (the NIMBY (Not In My Backyard) response),
2. geographically discounting unconsciously through not knowing out-of-boundary, indirect effects,
3. avoiding 'adding up' of many small parts to a regional or larger whole,
4. promoting a Biosphere II or space-station model as a viable alternative to one mimicking natural systems.

In this paper we develop three biophysical indicators—of depletion, dependence, and disturbance—and apply them to Chase County, Kansas. In Section 2 we discuss the indicators, including their connection with prior work. In Section 3 we discuss Chase County as an example region. In Section 4 we discuss data sources and calculate the indicators for Chase County for energy, water, soil, and nitrogen. In Section 5 we discuss economic flows for comparison and then use these to estimate indirect energy dependence, and in Section 6 we draw conclusions.

## 2. Proposed set of indicators: the 3 Ds.

We use three biophysical indicators which incorporate the above concerns, the 3 Ds. They are:

(1) Depletion index = − (present time rate of change of a resource stock)/(stock). This is applicable to non-renewable resources (e.g. coal), and potentially renewable ones being exploited at non-renewable levels (e.g. ground water). − (accrual) or 0 (stasis) is better; + (depletion) is worse.

(2) Dependence index = (gross import)/(internal use). This is applicable, for example, to food, energy, water, or medical services. Zero is better; + is worse. 'Imports' are not the same as 'inputs'. Imports, as applied here, includes resources that arrive in the community only as priced economic goods or services. For example, incident solar radiation is an input, but not an import. However, liquid propane originating outside of the system boundary and shipped in is both an input and an import.

(3) Disturbance index = (present flux)/(natural flux) − 1. This is applicable to e.g. nitrogen cycling, energy dissipation, or water throughflow. Zero (undisturbed) is best, $<0$ (reduced flux) or $>0$ (increased flux) are worse.

All three indicators are defined so that the non-depleting, independent, and undisturbed cases have an index of zero. The depleting, dependent, and (most) disturbed cases have positive indices. Depletion index compares a flow with a stock and has the dimensions of 1/time. If it is 0 or negative, the resource will last forever at the current level of use. If it is positive, its inverse is the lifetime at the present rate of depletion, which is termed the static lifetime. Dependence and disturbance indices both compare flows with flows and are hence dimensionless. The indicators are not strictly independent. The 'physical sustainability index' of Aguirre-Munoz et al. (2001) combines elements of all three.

Though hardly uncontroversial, depletion is the most concrete, least value-laden of the indicators.

Nonetheless, always there is the possible objection that increasing the efficiency of use or developing a substitute can compensate for depletion. Countering this view is the limit to substitution, especially of anthropogenic capital for natural capital (Daly, 1996; Costanza et al., 1997; Gowdy and McDaniel, 1999). Depletion can be applied to biological issues such as habitat and biodiversity, but we do not do so here.

Dependence is highly dependent on choice of physical boundary and of numeraire, and loaded with economic and political issues. Japan or Switzerland will have high dependence for imported food and energy. How does one reconcile viewing such a country as an ecological gamble (vulnerable for relying upon both long supply lines and distant, unseen depletion and disturbance) or as an economic paragon (proof of the benefits of comparative advantage and international trade)? This is fundamental to the global trade debate (Bhagwati, 1993; Daly, 1993). One can also ask that if being a (gross) importer is worse, is being an exporter better? While there is an argument for considering net imports as the basis of dependence, we use the gross approach because it spotlights off-site impacts, including those from interregional transportation, which would occur even for zero net imports. The transportation issue is often ignored in the analysis of ecotourism (Gossling, 1999); in the recent book 'Ecotourism and Sustainable Development' (Honey, 1999), the words energy, fuel, and transportation do not appear in the index.

Disturbance incorporates the notion that the fluxes (often 'cycles') in long-evolved, mature ecosystems with relatively little human influence are the appropriate benchmarks for sustainable systems with large human influence. Examples are fossil energy dissipation as compared with insolation (the ratio is $\approx 1$ for New York City vs. $\approx 10^{-4}$ globally (Woodwell and Hall, 1973, and updated by authors)), or the global nitrogen cycle (now speeded up by a factor of two (Smil, 1997; Tilman, 1998)). The premise that 'nature knows best' is arguable (Ausubel, 1996), although it is often claimed that nature provides services at lower economic cost than human technology would (Odum, 1996a). The Natural Step Foundation's principles stress disturbance in the sense of introduction of natural crustal material (e.g. lead) or man-made materials (e.g. PCBs) to the biosphere (Azar et al., 1996). To apply the idea of disturbance where there are incomplete cycles, we will discuss 'input' and 'output' disturbance. For example, for soil these could be wind-deposited inputs, and water-eroded losses, respectively. Table 1 lists more aspects and issues associated with the 3 Ds, as well as connections with similar concepts in economic and social issues.

While time is explicit only in depletion, all 3 Ds are sensitive to the choice of time step, which here is assumed to be 1 year. Phenomena with shorter characteristic times are not considered.

As stated, dependence raises the issue of off-site depletion and disturbance. Dependence thus can be expressed in direct or indirect terms. For example, a country may import little energy per se (i.e. directly) yet may import many energy-intensive goods. The energy was consumed abroad, yet can be thought of as the responsibility of the country importing and using those goods. This indirectness has been studied in detail in the field of (fossil) energy analysis (Bullard and Herendeen, 1975; Herendeen et al., 1981), leading to the term 'energy balance of trade' (Herendeen and Bullard, 1976; Herendeen, 1978). Howard Odum has stressed dependence in solar energy terms (Odum, 1971, 1983, 1996b; Odum et al., 1998). Decker et al. (2000) comprehensively review data and models for energy and materials flows through the world's largest cities, with an emphasis on atmospheric pathways. Indirect land use is captured in the concept of ecological footprint, which compares a nation's area with the productive land globally to support the consumption patterns of its population (Wackernagel and Rees, 1996; Wackernagel et al., 1999; World Wildlife Fund, 2000). The latter reference is a comparison of the footprints of about 150 nations. Ecological footprint shares several of the potential drawbacks of the 3 Ds; see the critique by van den Bergh and Verbruggen (1999).

Table 1
Definitions and aspects of the 3D's

| Indicator | Index definition | Typical numeraires | Analogous considerations for sustainability | | Difficulties |
|---|---|---|---|---|---|
| | | | Economic | Social | |
| Depletion | $-\frac{1}{\text{stock}}\frac{\mathrm{d(stock)}}{\mathrm{d}t} = (\text{static lifetime})^{-1}$ | Fossil fuels, soil, water, minerals, open space, habitat, capacity, biodiversity | Depleting productive capital | Deterioration of family, educational level, community cohesion | Efficiency of utilization affects depletion rate. 'Reserve' available depends on price |
| Dependence | gross inports/internal use[a] | Food, energy, fuel, raw materials, water, pollutants, labour, money, land | Balance of trade. Dependence on critical imports | Brain drain, migration | It is dependent on size of system, and choice of boundaries. It is difficult to measure. There is potential confusion between direct and indirect effects. That dependence is 'bad' contradicts argument for international trade |
| Disturbance | $\frac{\text{present flow}}{\text{'natural' flow}} - 1$ | Energy, nitrogen, water, carbon, sulfur | Boom/bust economic cycles | Change exceeding humans' ability to adjust | 'Nature knows best' is controversial and contradicts many human aspirations |

If the resource is assimilative capacity for emissions, then for consistency, we would say one is importing that capacity. Whether to use gross or net is discussed in text.

[a] This definition is appropriate for resources such as energy, ores, or water. If the resource is assimilative capacity for emissions, then for consistency we would say one is importing that capacity. Whether to use gross or not is discussed in text.

## 3. Example: Matfield Green and Chase County, Kansas

Our initial study area was Matfield Green, population approximately 50, a town at the edge of the Flint Hills of Kansas, 60 miles (mi) northeast of Wichita and 70 mi southwest of Topeka. In the past decade The Land Institute, Salina, Kansas, has established a presence in Matfield Green through:

1. purchasing and renovating several properties, including the school,
2. holding conferences and workshops on place-based education, prairie-based agriculture, settlement of the Great Plains, the viability of small communities, and broader issues (Jackson, 1994),
3. encouraging like-minded people to move to or retire in Matfield Green,
4. forging bonds with Matfield Green residents.

From 1900 to 1930 Matfield Green had from 150 to 200 residents, and at one time was a stop on the Santa Fe railroad. The Burlington Northern-Santa Fe freights now roar through around 50 times a day, but do not stop. Matfield Green's future could be as a conference center, retirement community, intentional low-impact agriculture community, or something else. Our intent was to determine the environmental impacts of Matfield Green today and in several possible future configurations. Ultimately confidentiality proved a barrier to data acquisition, especially because to determine indirect energy impacts of Matfield Green residents, we needed to know the details of where and for what people spend their money. We therefore expanded the study's geographic boundary to the county line.

Chase County is located in the eastern third of Kansas in the Flint Hills Uplands, as shown in Fig. 1. The county was chosen for four reasons. First, Chase County offered an apparent simplification of interacting human and ecological systems. It is sparsely populated with relatively little commercial, industrial, or residential development. The dominant industry is cattle grazing on never-plowed prairie. Second, Chase County is located 100 mi south of the Konza Prairie Long-Term Ecological Research (LTER) Area in Manhattan, Kansas. The Konza site has been used exclusively for research by Kansas State Univer-

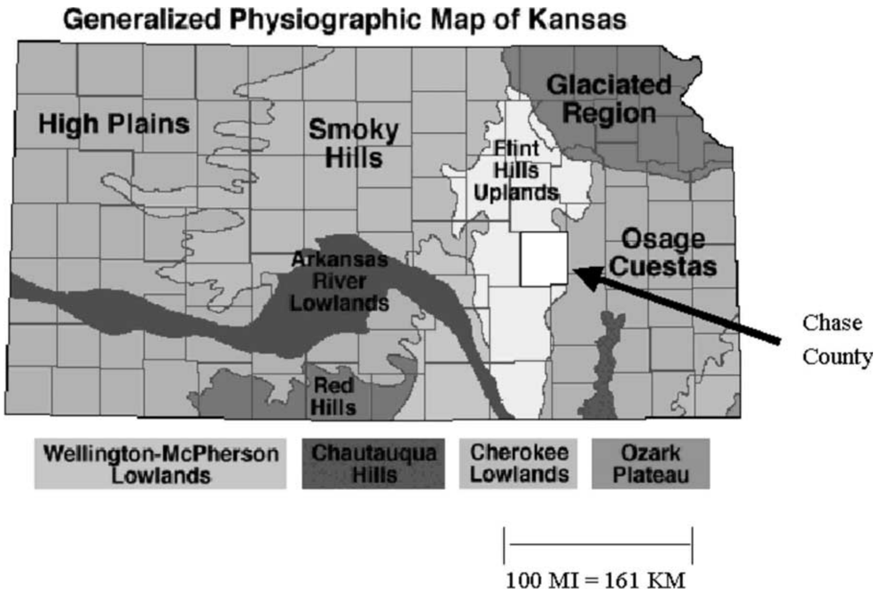


Fig. 1. Map of Kansas showing Flint Hills and Chase County (Kansas Geological Survey). Kansas is in the south central portion of the contiguous 48 US. It is 208 × 411 mi (335 × 662 km), with an area of 82 264 mi$^2$ (213 200 km$^2$). Central coordinates: 38.7 deg N, 98.4 deg W.

sity since 1971, and has been designated a National Science Foundation LTER station since 1980 (Knapp and Seastedt, 1998). The Konza is taken as the model of pre-settlement conditions of the tallgrass prairie in the Flint Hills. Third, the 1996 establishment of a National Park Service Tallgrass Prairie Park in Chase County has focused interest on the sustainability of natural resources use in the area. Still in its infancy as a national park, the Tallgrass Prairie Preserve could serve as an economic boon to the area, but with uncertain secondary impacts. Fourth, it contains Matfield Green.

Chase County covers nearly 500 000 acres (1 acre $= 4172$ m$^2 = 0.417$ ha; 1 mi$^2 = 640$ acres) and has a population of approximately 3000 people (US Bureau of Economic Analysis, 1995). This is 1 person per 170 acres, about 1/20 of the US average. The population peaked at 8200 in the 1890s and has declined steadily since (US Bureau of the Census, 1970; Burton, 1999, personal communication). The most common occupation is in the agricultural industries (22% of employed persons at least 16 years old), followed by retail trade (16%) and transportation (9%) (US Bureau of Economic Analysis, 1995). Two percent of the land is classed as urban. The remainder is agricultural, as follows: grazed rangeland (was never plowed, not seeded), 70%; grazed forest, 10%; cropland, 10%; pasture (has been plowed, periodically seeded), 8% (US Natural Resources Conservation Service, 1998).

The cattle industry is dominated by transient summer grazing, but also features year-round cow–calf ranches and small feedlot operations. Around 90% of the rangeland in the county is burned annually to maintain forage quality and suppress woody shrubs and trees. About 120 000 beef yearlings are shipped in each grazing season. Some are grazed using a seasonal continuous system; some, under intensive early stocking (Holder, 1999, personal communication, using the terminology of Vallentine, 1990). Approximately 15 000 mother cows are maintained year-round, birthing 13 500 calves each spring. Half are shipped out the following fall; the remainder, the next spring. In the winter (November–February), approximately 30 000 cattle are shipped into the county for maintenance. Most of these are shipped out after 3 months of winter feeding and a portion are held through the end of the following grazing season (September), depending on the number and condition of the original stock (Holder, personal communication).

Chase County contains the largest land holdings by single owners of all of the counties in the Flint Hills; 11 are greater than 6 mi$^2$. Fifty-nine percent of the land in economically viable ranching holdings $> 3$ mi$^2$ (1 mi$^2 = 2.59$ km$^2$) is owned by absentee owners and 17% is held by corporations (Kindsher and Scott, 1997).

## 4. Data and analysis

Four natural resources—soil, water, nitrogen, and energy—were evaluated in Chase County using the metrics of depletion, disturbance, and dependence. These resources were selected because they are necessary and because they are typically monitored by regular state or national programs. Most of the data were collected from Kansas state or national publications. When no detailed data were available, we used estimates by local resource professionals such as the county agricultural extension agent. These were checked against similar published reports.

Data analysis in this study is fundamentally bookkeeping. We do not repeat each resource's analysis in detail, but present one typical calculation, comment on data sources, and mention special cases. Full details are in Wildermuth (1999). Results are summarized in Table 2.

Chase County's inputs and outputs of each resource are given in Figs. 2–5. As explained below, nitrogen balances are provided for grazed lands (range, pasture, and grazed forest) and ungrazed lands separately.

### 4.1. Analysis—soil

For simplicity we consider only the productive A horizon of the soil profile as defined by the Soil Survey of Chase County (US Soil Conservation Service, 1974). All soil in the A horizon is considered homogenous because there are few data on

Table 2
Summary of indicators for Chase Country soil, water, energy, and nitrogen resources

| Resource[e] | Depletion[a] ($yr^{-1}$) | Static lifetime[b] (yr) | Dependence[c] | Distribution[d] | |
|---|---|---|---|---|---|
| | | | | Input form | Output form |
| Soil, grazed land[e,f,g] | $3.17\times10^{-4}$ to $-2.75\times10^{-5}$ | 3200 to $\infty$ | 0 | 0 | 0.4 |
| Soil, ungrazed land[g] | **$1.17\times10^{-3}$ to $1.41\times10^{-3}$** | **580 to 710** | 0 | 0 | **6.5** |
| Water[h,i] | 0 | $\infty$ | 0 | 0 | 0 |
| Oil[j] | **0.04** | **25** | **1** | | |
| Gas[j] | **0.07** | **14** | **1** | $2.55\times10^{-5}$ | **$\infty$** |
| Electricity[k] | NA | NA | **1** | | |
| Nitrogen, grazed land[l] | $2.88\times10^{-4}$ to $5.12\times10^{-2}$ | 3470 to $\infty$ | 0 | NA[m] | NA[m] |
| Nitrogen, ungrazed land[l,n] | $-1.4\times10^{-2}$ | $\infty$ | **0.59** | **12** | **8.1** |

Depletion, dependence, and disturbance indicators are 0 for no depletion, dependence, or disturbance. Bold indicates large differences from 0 for the 3 Ds, low values for static lifetime. NA = not applicable.

[a] A zero for depletion represents maintenance of a constant stock, a positive value represents decreasing stock, and a negative value represents increasing stock.

[b] For positive depletion, the inverse is the static lifetime. For depletion $\leqslant 0$, static lifetime = $\infty$.

[c] A zero for dependence represents self-sufficiency. A value greater than zero represents dependence on imports.

[d] A zero for disturbance represents equivalence of current and 'natural' resource flows. Either a positive or negative value represents a deviation.

[e] Soil includes only the A horizon, which is treated as homogeneous.

[f] Grazed land includes range, pasture, and grazed forest.

[g] Uncertainty reflects uncertainty in rates of soil formation.

[h] Assumes all streamflow is a free good.

[i] Effects of the upstream dam at Marion, Kansas, cannot be evaluated due to absence of long-term data including the pre-dam period.

[j] Assumes exponentially declining production; see Wildermuth (1999).

[k] Electricity is converted as 3413 Btu/kWh, with no accounting for thermodynamic losses in generation or transmission.

[l] Uncertainty due to the uncertainty in fixation by prairie vegetation.

[m] Details of long-term nitrogen cycling are not known at this level of detail.

[n] Assumes the same stock per acre as grazed lands.

in-horizon variation (Pimentel et al., 1995). The average depth of the A horizon in the county is 12 in. (1 in. = 2.54 cm) on cropland and 10 in. on rangeland (US Soil Conservation Service, 1974).

Estimated rates of soil formation by biogeochemical processes from inorganic substrate under grazed and cultivated conditions are heavily debated, but can be assumed to fall within the range of 0.1–0.6 ton/acre-yr (Logan, 1990; Pimentel et al., 1995). (1 ton = 909 kg; 1 acre = 4172 $m^2$.) Wind deposition and erosion are assumed to be negligible (US Natural Resources Conservation Service, 1997). In contrast, water erosion can be significant. Most of the rangeland is composed of native perennial grasses with extensive root networks that help prevent soil loss. As a result, the rate of water erosion on rangeland in the Flint Hills is approximately 0.56 ton/acre-yr (Holland, 1971). For comparison, the geological or long-term average rate of A horizon soil loss in the Flint Hills was around 0.4 ton/acre-yr (Koelliker, 1999, personal communication). Losses on cropland greatly exceed those on rangeland, but have decreased in the past 10 years because of improved farming practices. In 1982, the 50 000 acres of cropland in Chase County lost an estimated total of 543 800 $\pm$ 55 800 tons/yr of soil (i.e. 10 tons/acre-yr). By 1992, that total had been reduced to 145 600 $\pm$ 60 300 tons/yr (i.e. 3 tons/acre-yr) (US Natural Resources Conservation Service, 1997). We assume that all soil losses came from the A horizon.

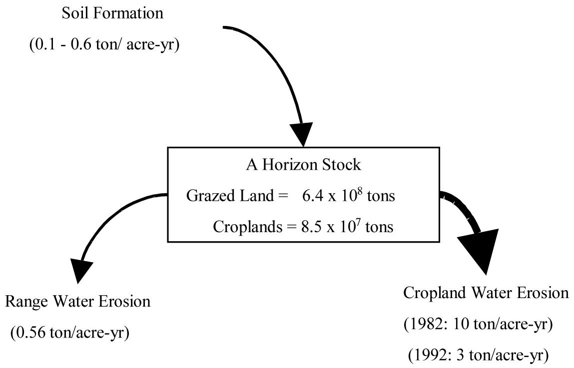


Fig. 2. Soil inputs and outputs for Chase County. Grazed lands are 90% of area; ungrazed lands, 10%. 1 ton = 909 kg, 1 acre = 0.417 ha.

Below are the calculations for depletion, dependence, and disturbance for soil in Chase County. Fig. 2 shows the soil flows. The results of these calculations, as well as for the other three resources, are summarized in Table 2.

Rate of change of soil stock, $dS/dt$:

*Grazed land:* Using the maximum soil formation rate of 0.6 ton/acre-yr: $dS/dt = (440\,000$ grazed acres)(0.6 ton formed − 0.54 ton eroded)/(acre-yr) = + 17 600 tons/yr (best case, accrual). Similarly, using the minimum soil formation rate of 0.1 ton/acre-yr: $dS/dt = -202\,400$ tons/yr (worst case, loss).

*(Ungrazed) cropland:* Using the maximum soil formation rate of 0.6 ton/acre-yr: $dS/dt = (50\,000$ cropped acres)(0.6 ton formed − 3.0 ton eroded)/(acre-yr) = − 120 000 ton/yr (best case, loss). Similarly, using the minimum soil formation rate of 0.1 ton/acre-yr: $dS/dt = -145\,000$ tons/yr (worst case, loss).

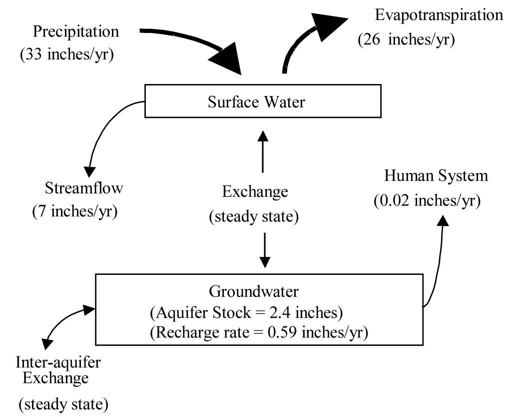


Fig. 3. Water inputs and outputs for Chase County. 1 in. = 2.54 cm.

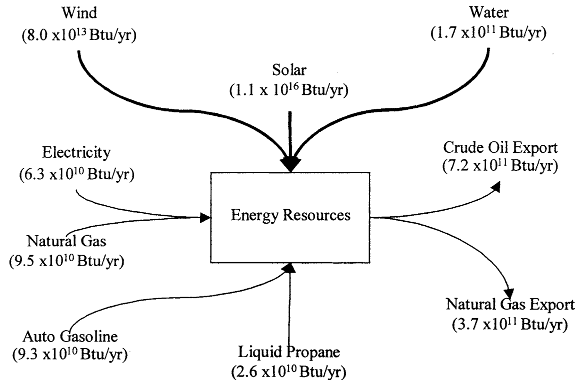


Fig. 4. Energy inputs and outputs for Chase County. County has oil and gas wells but no refining capacity. 1 Btu = 1055 J.

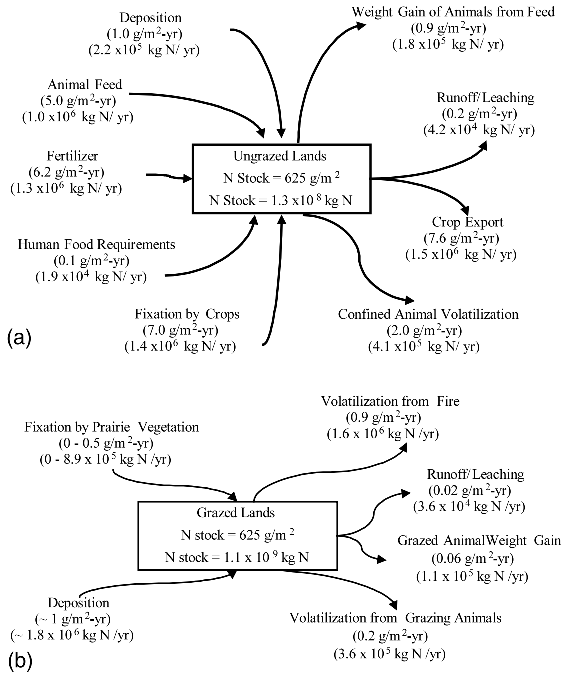


Fig. 5. (a) Nitrogen inputs and outputs for Chase County ungrazed lands. 'Human food requirements' is nitrogen content of imported food. (b) Nitrogen inputs and outputs for Chase County grazed lands.

Soil stock, $S$:

Assume a bulk density of 1.25 g/ml.

*Grazed land:* 10 in. deep × 450 000 acres yields $6.4 \times 10^8$ tons.

*(Ungrazed) cropland:* 12 in. deep × 50 000 acres yields $8.5 \times 10^7$ tons.

Values of the 3 Ds:

*Depletion, grazed land:* Using the best case, accrual: $-(\mathrm{d}S/\mathrm{d}t)/S = -(+17\,600$ tons/yr)/($6.4 \times 10^8$ tons) $= -2.75 \times 10^{-5}$/yr. Negative depletion is accrual.

*Depletion, (ungrazed) cropland:* Using the best case, which is still a soil loss: $-(\mathrm{d}S/\mathrm{d}t)/S = -(-120\,000$ tons/yr)/($8.5 \times 10^7$ tons) $= 1.41 \times 10^{-3}$/yr. Positive depletion is loss.

*Dependence for grazed and ungrazed land:* Gross imports of soil are zero; therefore dependence is 0.

*Disturbance:*

Input form: No change in soil formation or deposition; therefore 0.

Output form:

$$\frac{\text{erosion}_{\text{current}}}{\text{erosion}_{\text{presettlement}}} - 1$$

$$= \frac{(90\%\ \text{grazed})(0.56\ \text{ton/acre-yr}) + (10\%\ \text{ungrazed})(3.0\ \text{ton/acre-yr})}{(100\%\ \text{of original prairie})(0.4\ \text{ton/acre-yr})} - 1 = 2.01 - 1$$

$= 1.01$ (average for all lands in Chase County).

Similarly, disturbance $= (0.56/0.4) - 1 = 0.4$ on grazed land and $(3.0/0.4) - 1 = 6.5$ on (ungrazed) crop land.

### 4.2. Analysis—water

Chase County contains portions of six different USGS watersheds, most in either the Upper Cottonwood or Lower Cottonwood basins. All are part of the Arkansas-White-Red USGS hydrological unit (US Geological Survey, 1997). The Cottonwood River flows from west to east and has been dammed at Marion, just west of the county line, since 1968. The dam has altered the annual hydrograph, but there are no pre-dam data available for comparison.

Chase County's average precipitation of 33 in./yr (National Oceanic and Atmospheric Administration, 1990) goes to evapotranspiration, streamflow, or aquifer recharge. For consistency, in Fig. 3 water volumes are converted to depth, assuming uniform distribution over the entire county. All principal aquifers are alluvial along the Cottonwood River and its tributaries. Because of negligible withdrawals (0.02 in./yr) and balanced exchange with connected ground and surface waters (O'Connor, 1951; Kansas Department of Agriculture, 1995a,b), the aquifers are considered saturated, containing 98 400 acre-feet (2.4 in.) and having an annual recharge capacity of 23 200 acre-feet/yr (0.59 in./yr) (Hansen, 1991). USGS gauging data show that average net streamflow exports about 7 in./yr, leaving 26 in./yr available for evapotranspiration. These data are used to calculate the 3 Ds for water given in Table 2.

### 4.3. Analysis—direct energy

In this section we analyze only direct energy flows-fuels and electricity, as shown in Fig. 4. (In Section 5 we estimate indirect energy flows, the energy to make imported and exported goods.) Renewable energy sources—solar, wind, and some water—are abundant, but are almost entirely untapped. The average daily solar radiation upon a horizontal surface is 4.5 kWh/m$^2$ (US Department of Energy, 1997), equivalent to a potential of $1.1 \times 10^{16}$ Btu/yr over the surface of the county (1 Btu = 1055 J). The gravitational potential energy of flowing water in the county totals $1.7 \times 10^{11}$ Btu/yr if the flow as given by USGS gauging stations is averaged over the entire county. The Flint Hills are noted for their winds, which are some of the most consistently strong ($\sim 16$ mph = 26 kph) in the US. Wind could deliver $8.0 \times 10^{13}$ Btu/yr to Chase County (evaluated for turbines with 50 m hub height on a 500 × 250 m grid, extracting 25% of the wind energy and with 25% power loss (Elliott et al., 1991).

The county is also endowed with natural gas and crude oil, nearly all of which is exported. 1987–1997 average oil production was 124 735 bbl/yr (Kansas Geological Survey, 1999), or $7.23 \times 10^{11}$ Btu/yr (1 bbl = 42 gallon; 1 gallon = 3.78 l). For the same period, the average gas production was $373 \times 10^6$ ft$^3$, or $3.73 \times 10^{11}$ Btu/yr (1 ft$^3$ = 28.5 l). Production has been declining roughly exponentially for the past 25 years. Extrapolation of this trend yields remaining stocks of $2.5–3 \times 10^6$ bbl of oil and $\sim 4 \times 10^9$ ft$^3$ of gas (Wildermuth, 1999).

Despite this internal stock, Chase County imports nearly all of its direct fossil energy and electricity. An average of $18.5 \times 10^6$ kWh/yr ($6.31 \times 10^{10}$ Btu/yr) of electricity was provided to the county over the period 1988–1997 (Goeckel, 1998, personal communication; Schreiber, 1998, personal communication). In 1995, $95\,302 \times 10^3$ ft$^3$/yr ($9.5 \times 10^{10}$ Btu/yr) of natural gas was used within the county (Wolff, 1998, personal communication). Liquid propane is a common fuel source for much of the rural county, but no central record of usage is maintained. An estimate of 1000 gallons/yr-household was derived by surveying local distributors. Three hundred and nine households in the county relied on LP for heating (US Bureau of Economic Analysis, 1995), leading to an estimated consumption of $2.6 \times 10^{10}$ Btu/yr. Auto and light truck fuel consumption was calculated by assuming 0.5 auto per person, 10 000 mi traveled annually per vehicle, and an average road fuel efficiency of 20 mpg, giving $9.3 \times 10^{10}$ Btu/yr. The resulting 3 Ds for energy are given in Table 2.

### 4.4. Analysis–nitrogen

Nitrogen is the most difficult of the numeraires because of its complicated chemistry. Grazed lands (grazed forest, rangeland, and pasture) were separated from non-grazed lands (urban and crop lands); see Fig. 5a and b. For grazed land, the implicit comparison is between pre-settlement grazing by wide-ranging bison, elk, deer, and antelope on a prairie that burned every few years; and the current grazing by more confined cattle on a prairie burned purposely every year. The nitrogen balance on range depicted in Fig. 5a follows the findings of Hobbs et al. (1991) with minor modification. They concluded that N in Flint Hills prairie under grazing is approximately in balance and that with annual burning, grazing may determine whether N accumulates or declines. Dodds et al. (1996) reported similar inputs and outputs for ungrazed tallgrass prairie, but included minor leaching/runoff losses that were incorporated into our calculation. The N content (stock) of the top 25 cm ( = 10 in.) of Flint Hills soil is taken as 625 g/m$^2$ (Blair et al., 1998).

The effects of grazing by large ungulates on N fluxes are the least well understood and least studied influences on nutrient cycling in the tallgrass (Blair et al., 1998), making a detailed account of long-term N cycling difficult. Flint Hills grazed prairies have been studied under controlled fire frequency and grazing intensity, but the pre-settlement pattern is not known as well (Owensby, 1998, personal communication).

N inputs to ungrazed lands include feed requirements of both cattle and people, fixation by leguminous crops, N deposition, and synthetic fertilizer application. Net cattle feed requirements are nutritional requirements of fed cattle (Thomas and Gilliam, 1977) minus the portion of those requirements met by internal hay and silage production (Kansas Agricultural Statistics Service, 1999; Legg and Meisinger, 1982). We assume that all N in human diets was imported; gardening and farmers' market sales were negligible. Fixation by crops (including forage) was determined by multiplying crop production by standard crop N fixation rates (Kansas Agricultural Statistics Service, 1999; Jordan and Weller, 1996). Fertilizer inputs were estimated from recommended crop applications in the region (Holder, 1999, personal communication). Deposition is difficult to separate from resuspension (Blair et al., 1998), but we have assumed an N deposition of $\sim 1$ g/m$^2$-yr (Jordan and Weller, 1996).

N exports from ungrazed land consist of crop exports, runoff/leaching, weight gain of cattle from feed, and volatilization. Sewage is not a significant export because it is treated in lagoons within the county. N in crop exports is calculated in the same way as for crop imports. Using conversion efficiencies of feed to weight, feed to excretion, and excretion to volatilized N, we determine exports in fed weight gain and manure volatilization (Thomas and Gilliam, 1977). Jordan and Weller (1996) provide a nitrate discharge 0.20 kg N/ha-yr from the entire Arkansas-White-Red basin. This figure is an average of runoff from dryland, pasture, and cropped land. Goolsby et al. (1999) obtain identical values of 0.5 kg N/ha-yr from measurements of the Kansas River at Desoto, Kansas, and the Arkansas River at Tulsa, Oklahoma. These drainages cover a large part of Kansas; we use the latter value. One might argue that because Chase County's ungrazed land is intensively row-cropped, an even higher figure is appropriate. However, because only 10% of the county is cropped, even doubling the figure would change N depletion and disturbance by less than 1%, so further concern is unwarranted here. Results of calculating the 3 Ds for nitrogen are given in Table 2.

## 5. Economics and indirect energy

The dependence index suggests economic questions as well as raising the issue of indirect impacts. In this section we use aggregated economic data for Chase County to estimate indirect energy dependence. Economic data are from several runs (Leatherman, Kansas State University, personal communication) of the commercial input–output-based analysis system IMPLAN (Minnesota IMPLAN Group, Inc., IMPLAN System 1940 South Greeley Street, Suite 101, Stillwater, MN 55082). IMPLAN produces economic input–output tables at the county level for the entire US. In our case we use a 12-sector level of detail (livestock; crops; other agriculture; mining (including energy); construction; manufacturing; transportation, communication, and public utilities; wholesale and retail trade; tourism-sensitive activities; financial, insurance, and real estate; other services; and government). For comparison we also list two urbanized areas in Kansas: Sedgwick County, which includes the city of Wichita, and Johnson and Wyandotte Counties, which include Kansas City. Wichita is 60 mi from Matfield Green, and some Matfield Green residents commute to it. Kansas City is 150 mi from Matfield Green.

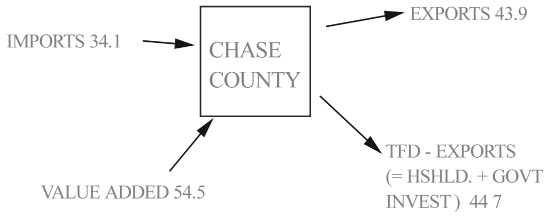


Fig. 6. 1996 monetary flows (in million 1996 dollars per year) for Chase County. Source: John Leatherman, personal communication. TFD = total final demand. HSHLD = households.

Fig. 6 shows the monetary flows in Chase County in 1996. Table 3 shows that Chase County produces about half as much value added per unit of import as Sedgwick or Johnson and Wyandotte Counties, and has a value added per capita about half as great. Sedgwick County is 117 times more densely populated, and creates 224 times as much value added per acre. While not surprising, these data verify that if: (1) Chase County remains dedicated mostly to range beef production, (2) the price of meat stays somewhere near today's level, (3) residents desire a per-capita value added approximating the national average; then Chase County must be relatively sparsely populated. This is consistent with the population's steady decline in the last century.

Fig. 7 shows total (direct + indirect) fossil energy flowing through Chase County in 1996. The monetary flows have been converted to total fossil energy requirements using energy intensities determined for the entire US economy (Casler, 1991). This application of energy analysis uses older data and requires approximations and assumptions which have been acknowledged (Bullard and Herendeen, 1975; Bullard et al., 1978), so the numbers are approximate. We see that Chase County's oil and gas wells send essentially their entire output out of the county. The energy embodied in imported non-energy goods ($3.99 \times 10^{11}$ Btu/yr) exceeds the imported direct energy ($2.77 \times 10^{11}$ Btu/yr); it is 59% of the import total of $6.76 \times 10^{11}$ Btu/yr. Therefore, counting both direct and indirect energy inputs would

Table 3
Comparison of Chase, Sedgwick, and Johnson and Wyandotte Counties, Kansas

| | Chase County, Kansas (Matfield Green) | United States | Sedgwick County, Kansas (Wichita) | Johnson and Wyandotte Counties, Kansas (Kansas City) |
|---|---|---|---|---|
| VA/imports ($/$) | 1.60 | 7.94 | 3.13 | 2.86 |
| VA/area ($/yr-acre) | 110 | 3308 | 24 654 | 50 276 |
| VA/person ($/yr-person) | 18 793 | 28 891 | 36 278 | 28 891 |
| Population density (persons/acre) | 0.0059 | 0.11 | 0.68 | 1.42 |
| Population density with respect to US average | 0.054 | 1.0 | 6.2 | 12.9 |

1996 data from John Leatherman, Kansas State University (personal communication), and from Bureau of Economic Analysis, US Department of Commerce. 1 acre = 0.41 ha.

more than double the energy dependence of Chase County as calculated in Section 4. That direct energy is 40–50% of total has been seen in household consumption patterns in Norway (Herendeen, 1978), the US (Herendeen et al., 1981), and the Netherlands (Biesiot and Noorman, 1999). In passing, we note that if we use embodied energy flows, dependence = (2.77 + 3.99)/3.67 = 1.82. If we use the Proops et al. (1999) approach, which uses net rather than gross imports, we would find that dependence = (2.77 + 3.99 − 10.9 − 3.08)/3.67 = − 1.97.

## 6. Conclusions

Table 2 lists the calculated 3 Ds for Chase County for soil, water, (direct) energy, and nitrogen. Bold cells indicate large differences from 0 for the 3 Ds or low values for static lifetime. These occur for depletion of fossil fuel and soil, dependence on energy and nitrogen imports, and disturbance of ungrazed land. Grazing as practiced in Chase County does not produce large values for the 3 Ds.

Table 3 summarizes economic data, and Fig. 7 summarizes the flow of direct + indirect energy. We see that economic yield per acre from grazing is low compared with other economies involving higher human densities.

For soil, there is relatively little depletion on grazed lands (static lifetime is at least 3200 years). For ungrazed (mostly cropped) lands there is more depletion (static lifetime at least 580 years), which is comparable with black soil row-cropping in, e.g. Illinois (Herendeen and Mukherjee, 1996). Dependence is zero. Output disturbance, i.e. gross soil export, is 0.4 for grazed land, but 6.5 for ungrazed (row-cropped, feedlot, urban area): un-

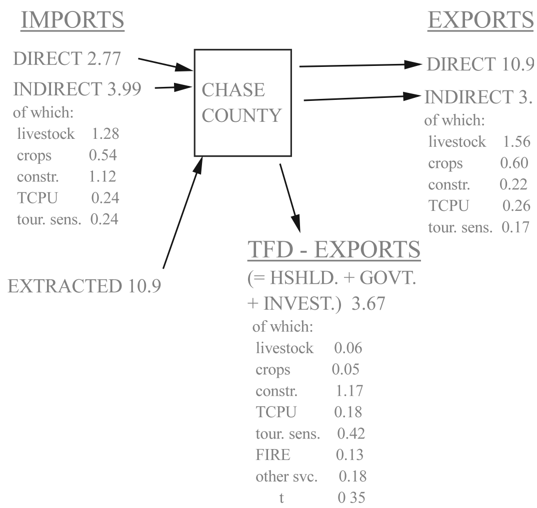


Fig. 7. Embodied energy flows ($10^{11}$ Btu/yr) for Chase County. The economic flows in Fig. 6 have been multiplied by energy intensities from Casler (1991). Figures have been adjusted to achieve approximate county embodied energy balance. TFD = total final demand. HSHLD = households. TCPU = transportation, communication, (non-energy) public utilities. Tour[ism] sens[itive] = food stores, automotive services, restaurants, hotels, amusement and recreation. FIRE = financial, insurance, real estate.

grazed land is substantially contributing eroded soil to watercourses.

For water, all 3 Ds are zero: no depletion, no dependence, and approximately no disturbance. While the County's aquifers are thin, today's withdrawal is only a few percent of potential recharge. Today, Chase County is not mining its ground water.

For direct energy, Chase County is depleting its oil and gas for export. Static lifetimes are 25 years for oil and 14 years for gas. Because Chase County does not have oil refining or gas cleaning facilities, it imports all the cultural energy it consumes, and therefore has a dependence of 1. Compared with solar inputs (solar itself, wind, water), the county's use of fossil fuel is small; the input disturbance is $2.5 \times 10^{-4}$, approximately one-tenth of that for the US as a whole. In the pre-settlement state, it exported no fossil energy, so output disturbance is infinite. Chase County is now exporting 3.7 times as much energy as it uses. If that export were diverted to internal use, static lifetimes would be roughly quadrupled.

For total (direct + indirect) energy, dependence is more than doubled, because the energy to produce Chase County's imported non-energy goods and services exceeds the energy imported directly.

For nitrogen, depletion is essentially zero on grazed land. On ungrazed land there is accrual. Accrual could result from building of N stocks in either waste lagoons or soil pools, or is a result of underestimation of N volatilization from waste lagoons. Grazed land has zero dependence, while ungrazed land has a dependence of 0.59, dominated by fertilizer and imported feed. Disturbance for grazed land is approximately zero, though characterizing the pre-settlement prairie for comparison is uncertain. For ungrazed land, input disturbance is approximately 12, again dominated by fertilizer and feed inputs. Output disturbance is approximately 9, dominated by exported crops.

That grazing on unbroken land in a rural, sparsely populated area is relatively gentle environmentally, but not lucrative per land unit, is probably no surprise to most readers. Range beef production roughly mimics the pre-settlement pattern in Chase County, and it has relatively low impact as measured by the 3 Ds for soil, water, and nitrogen. Modern row agriculture and generalized fossil fuel use have relatively large impacts as indicated by the 3 Ds for energy and nitrogen. Chase County has 90% of its area in range beef production because of its terrain, soil, and climate, but this is allowed by its low human density. One can speculate that if Chase County were to become much more populated, to maintain or increase per capita value added would likely require higher Ds. This indicates the direction for future research: to perform similar analyses for a Kansas City, Singapore, or Nairobi, or a Hudson or Niger watershed, over a gradient of densities and economic development, with a possibly modified or expanded list of numeraires.

Further analysis is appropriate, but a serious problem with indicators, particularly those outside of conventional economics, is that they are not often used. To address this we are actively involving, from the beginning, both academic and practicing professional planners in analyzing an urban area (Champaign, Illinois). We feel that indicators such as the 3 Ds (especially dependence in the case of cities) are necessary to honest planning for sustainability, but they need a connection with reality that this interaction should provide.

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