Thermodynamics of Agricultural Sustainability: The Case of US Maize Agriculture

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This paper considers the local, field-scale sustainability of a productive industrial maize agrosystem that has replaced a fertile grassland ecosystem.

Using the revised thermodynamic approach of Svirezhev (1998, 2000) and Steinborn and Svirezhev (2000), it is shown that currently this agrosystem is unsustainable in the U.S., with or without tilling the soil. The calculated average erosion rates of soil necessary to dissipate the entropy produced by U.S. maize agriculture, 23–45 t ha$^{-1}$ yr$^{-1}$, are bounded from above by an experimental estimate of mean soil erosion by conventional agriculture worldwide, 47 t ha$^{-1}$ yr$^{-1}$, (Montgomery, 2007). Between 1982 and 1997, US agriculture caused an estimated 7–23 t ha$^{-1}$ yr$^{-1}$ of average erosion with the mean of 15 t ha$^{-1}$ yr$^{-1}$ (USDA-NRCS Database). The lower mean erosion rate of no till agriculture, 1.5 t ha$^{-1}$ yr$^{-1}$ (Montgomery, 2007), necessitates the elimination of weeds and pests with field chemicals—with the ensuing chemical and biological soil degradation, and chemical runoff—to dissipate the produced entropy. The increased use of field chemicals that replace tillers is equivalent to the killing or injuring of up to 300 kg ha$^{-1}$ yr$^{-1}$ of soil flora and fauna. Additional soil degradation, not calculated here, occurs by acidification, buildup of insoluble metal compounds, and buildup of toxic residues from field chemicals. The degree of unsustainability of an average U.S. maize field is high, requiring 6–13 times more energy to reverse soil erosion and degradation, etc., than the direct energy inputs to maize agriculture. This additional energy, if spent, would not increase maize yields. The calculated “critical yield” of “organic” maize agriculture that does not use field chemicals and fossil fuels is only 30 percent lower than the average maize yield of 8.7 tons per hectare (~140 bu/acre) assumed here. This critical yield would not likely be achieved and sustained by large monocultures, but might be achieved by more balanced organic polycultures (Baum et al., 2008).

Keywords: ecosystem, organic, irreversible, process, entropy, energy

I. INTRODUCTION

On April 8, 2008, some 484,000 web pages were flagged in search for “sustainability definition.” Why so many definitions? Perhaps, because it is very difficult to provide a physically, biologically, and chemically consistent definition of sustainability and translate its linguistic expression into a self-consistent and comprehensive mathematical model. This paper attempts to accomplish a little of both, and apply a specific, entropy-based definition of sustainability to a narrow class of ecosystems encompassed by agriculture and, in particular, maize agriculture. First let us introduce three preliminary definitions:

1. An ecosystem is a community of living organisms that occupy a given space and time, and their abiotic substrate (soil, water, and air).
2. Exergy (free energy referenced to the environmental conditions) is a part of energy that can be converted to work of a rotating shaft; one can think of exergy as an equivalent of electricity.
3. Entropy is that part of energy that must be dissipated as heat and cannot be converted to work of a rotating shaft.

Thermodynamics can provide quantitative insights into the sustainability (or lack thereof) of the simplified, “permanently immature” agricultural ecosystems that select for rapid growth (maximum rate of exergy production) and edibility of a single crop plant; are susceptible to attack by insects, worms, animals, and disease; have widely open nutrient flows; and are reset every year to a state of barren soil partially covered with remnants of dead plants (early succession).

Eugene Odum (1969) developed a theory of ecosystem succession and noted that—given enough time measured in years, decades and centuries—maturing ecosystems develop a strategy of “maximum protection,” or maximum support of their complex metastable biomass structures against environmental perturbations, see Figure 1. The seminal paper by Odum has caused much controversy and a flurry of research in theoretical ecology, see (Holling, 1986; Ulanowicz, 1986; Jorgensen, 1992; Schneider and Kay, 1994), just to name a few. Thirty years later, Kutsch et al. (1998) measured 25 key properties of ecosystems at different stages of maturity and quantified the maturation process starting from two field systems (continuous maize, and maize + crop rotation), and proceeding through a dry and wet grassland, a beech forest, and a wet alder forest. The crop fields represented pioneer stages, the grasslands an intermediate stage, and the forests a mature stage of ecosystem development.

In particular, the “permanently immature” continuous maize system was characterized by the least number of species, a non-detect presence of soil fauna, the smallest soil microbial mass, the smallest total soil organic carbon (TSOC), the highest phytomass in systems with no trees, the highest net photosynthetic rate, the highest flux of net primary production relative to TSOC, the highest ecosystem respiration relative to TSOC, and a non-detect production of soil fauna. The authors concluded that the agricultural maize systems represent the “perpetuated pioneer stages of secondary succession,” and are driven to a high yield by the external anthropogenic energy and chemical inputs.

Ecosystems are inherently dynamic and follow the four-stage cycles$^2$ proposed by Odum (1969) and refined by Holling (1986), see Figure 2. The first two stages determine ecosystem succession: Early-to-Middle Succession or Renewal (1), and Middle-to-Late Succession or Exploitation (2). The Climax or Conservation stage (3) is metastable and may not persist indefinitely$^3$. Stage (4) is a discontinuous ecosystem simplification, called Creative Destruction, by fire, floods, storms, hurricanes, pests, pathogens, or an abrupt climate change. After being thrown back to Stage (1), the ecosystem reorganizes itself, as resources that were released in the Destruction Stage (4) are made available for the consecutive Exploitation Stage (2). These four stages make the clockwise-oriented envelope curve depicted in Figure 2.

$^2$The idealized cycle shown here may be considered as a smoothed envelope of a set of chaotic loops of various lengths that fill its interior. The Lorentz strange attractor provides a good analogy for these “space-filling loops.”

$^3$The undisturbed tropical rainforests have persisted for several thousands of years.
FIG. 1. Odum’s (1969) comparison of the energetics of succession in a forest and a laboratory microcosm. $P_G = GPP$, gross primary production; $P_N = NPP$, net primary production; $R$, respiration; $B$, total biomass. Note that with time each ecosystem achieves a metastable climax characterized by zero net ecosystem production ($NPP = GPP - R \approx 0$). Both idealized ecosystems are not thrown from their climaxes back to the origin by a fire or pathogen. In real life, this always happens sooner or later. Typically, liter-sized microecosystems contain two or three species of non-flagellated algae and one to three species each of flagellated protozoans, ciliated protozoans, rotifers, nematodes, and ostracods; a system derived from a sewage pond contained at least three species of fungi and 13 bacterial isolates. Reproduced with the permission of AAAS.

Kay et al. (1999) reinterpreted the Odum–Holling cycle in terms of exergy accumulation and flow, thus providing an ecosystem-centric thermodynamic framework required for this paper. In the early exploitation stage (2), given sufficient nutrients, water, and genetic information, dissipative processes emerge that sequester the energy of sunlight. The rate of sequestration increases with the accumulation of biomass and exergy. A positive feedback loop develops that helps the ecosystem to acquire ever more structure and connectivity and to store ever more exergy. The First Thermodynamic Branch (late 1 $\rightarrow$ 2 $\rightarrow$ 3) uses the sun as the main source of energy. With the growing accumulation of exergy (an increasing store of interconnected biomass), the probability of emergence of clusters of fire, pests, etc. also increases. In State 3, the system is as far from thermodynamic equilibrium as it ever gets. Stage 4 brings the ecosystem closer to thermodynamic equilibrium. The higher the density and interconnectedness of biomass, the higher the probability of the fire or pathogen clusters merging and forming a percolating cluster (Stauffer and Aharony, 1994). For example, the August 1988 firestorm obliterated much of the forest in the Yellowstone National Park after nearly 100 years of fire suppression.4

Agrosystems are artificially driven to the maximum growth rate stage (2) in the shortest possible time by mechanical work, fertilizers, pesticides, herbicides, etc., as well as fire protection. In the case of agrosystems, specialized pathogens always emerge and provide the most probable path 2 $\rightarrow$ 4 $\rightarrow$ 1. As shown by May (1985) with the use of simple population genetics, no pesticide can ever stop a new destructive pathogen from emerging. These pathogens will destroy their target crop monocultures unless new field chemicals are invented fast enough.5

In the renewal stage, the exergy that was stored in the dead biomass is made available for reuse. Thus ecosystems not only recycle mass within each of the stages 1, 2, and 3, but also recycle mass to the fullest extent possible between the stages. The Second Thermodynamic Branch 3 $\rightarrow$ 4 $\rightarrow$ early 1 uses the chemically stored exergy as the main source of energy. In the reorganization stage, decomposition processes that consume the previously stored exergy provide feedstock for the First Thermodynamic Branch.

4Management objectives that focus on maximizing biomass accumulation, thus preserving the ecosystem in State 3, can be overwhelmed by the emergence of a fire or pathogen. These objectives can lead to a larger loss over a larger area than would naturally occur because they encourage excessive accumulation of exergy that cannot be consumed or degraded by the structures that are preserved (Bass, 1998; Kay et al., 1999).

5In his review, Professor Chapella observes: “No need to go into May’s description of ecological processes—this description is challenged by observation, although it makes good material for the thermodynamic analysis at hand. Personal communication, Nov. 20, 2007. Professor Pimentel conurs, personal communication, Nov. 22, 2007. The question still remains: What happens when a pathogen emerges for which we have not prepared in advance?
II. SUSTAINABILITY

This paper is about the local sustainability of an ecosystem and its environment. In 1990, Svirezhev defined, and later published (1998, 2000), thermodynamic sustainability of an ecosystem as follows:

1. Any ecosystem is an open thermodynamic system, exchanging mass and energy with its environment.
2. A metastable maximum-biomass steady state (climax) of an ecosystem exists when the entropy production inside the ecosystem is balanced by the entropy export from the ecosystem to its environment.
3. This entropy export is driven by the solar entropy pump.

Three corollaries follow from this definition: (1) For the "solar entropy pump" to work, only heat can be transferred from the ecosystem to the environment. This heat is then radiated into space filled with the Big Bang radiation at almost 3 K. (2) Over a sufficiently long time interval, almost all mass must be recycled in the ecosystem, and some is buried, see Patzek (2007) for more discussion. (3) All industrial monocultures violate Condition 2 for different reasons and are unsustainable, see Appendix D for more discussion.

Ulanowicz (1998) proposed an information- or entropy-based necessary condition of sustainability of an ecosystem. Ten years later, Ulanowicz et al. refined this condition (2007). Using the authors’ notation:

1. The capacity for a system to undergo evolutionary change or self-organization is the sum of two aspects: It must be capable of exercising sufficient directed power to maintain its functionality over time (Efficiency, A). Simultaneously, it must possess enough capability for flexible actions (Resilience, Φ) that can be used to meet the exigencies of novel disturbances.
2. The system Efficiency, A, is a matrix product of the total system mass flow rate (throughput), T, and the deterministic constraints, X, quantified by mutual information about the system components: $A = TX$.
3. The system Resilience, Φ, is the product of T and the conditional entropy of the system, Ψ, which is related to the total indeterminacy of the system (the absence of order or information), $H$: $Ψ = (H - X)$, $Φ = TΨ$.
4. The set of constraints, X, quantifies all that is regular, orderly, coherent and efficient. It encompasses all the conventional concerns of science. By contrast, Ψ represent the lack of those same attributes, or the irregular, disorderly, incoherent and inefficient behaviors.
5. Sustainability is the probability that a given system achieves its optimal balance between Efficiency and Resilience. At the community level a system is therefore considered 100% sustainable whenever that balance attains the optimal mix (assuming that there is a single optimal mix), see Figure 3. That is, in order to remain sustainable, a natural ecosystem must possess a propitious ratio of order to flexibility. From available data, it appears that this ratio is somewhere near 2:3.

An important corollary to the Ulanowicz et al.’s (2007) necessary condition of sustainability is that an ecosystem cannot survive unless it is biodiverse, disorderly, and somewhat inefficient. The giant monocultures favored by the current “green revolution” agriculture7 are destined to a certain long-time failure precisely because they are streamlined and efficient at an extreme, but lack biodiversity and, thus, resilience. Ulanowicz et al. illuminate perhaps the most essential quality of sustainability: it depends less on what is, than on what is not, i.e., on the absence of information: the system entropy.

Patzek gave (2004a) a global definition of sustainability. A cyclic process is sustainable if and only if

1. It is capable of being sustained, i.e., maintained without interruption, weakening or loss of quality “forever,” and
2. The environment on which this process feeds and to which it expels its waste is also sustained “forever.”

Patzek’s definition relies on an operational definition of “forever,” a few thousand years at most for anthropogenic systems, and perhaps another 50–200 years for the well-managed, intensive “green revolution” agriculture7 in the US and the tropics. Identical corollaries follow from Patzek’s definition. All agricultural processes that rely on external (fossil fuel) inputs are not cyclic and cannot be sustainable. This is not to say that humans

6Dr. Robert Ulanowicz, private communication, April 7, 2008.
7The high N-P-K treatments and an increasingly massive incorporation of crop residues into the soil at the the Morrow test site, lead to a prediction of the complete depletion of soil organic carbon in 290, 320, and 560 years, respectively, see Table 2 in (Khan et al., 2007). Agriculture was strong in the U.S. Midwest in 1860, some 150 years ago. Soil fertility crashes long before all soil organic carbon is depleted, see (Stocking, 2003; Wilhelm et al., 2007).
do not know how to operate high-yield sustainable agriculture with no fossil fuel inputs. This agriculture evolved and operated in China for over 2000 years with little or no destruction of the densely populated agrosystems (King, 1911). Its main requirement was to recycle everything locally, thus satisfying the necessary and sufficient conditions in Patzek’s definition. At the same time, in China, during the two thousand year period (between 108 BCE and 1910) there were 1828 years (over 90 percent of the total) in which famines involved at least one province of the country, see Ponting, p. 102 (2007). Ponting also documents the often recurring and widespread famines of Europe in the 2000 years prior to the 20th century.

Svirezhev’s definition leads to a particularly simple quantification of the degree of unsustainability in terms of the local entropy production and flow rates in the system, and the minimum, i.e., reversible, local restoration work. The concept of global reversible restoration work was used by Patzek (2004) and Patzek and Pimentel (2006) to define the degree of global unsustainability of the U.S. maize-ethanol agrosystem and its supporting industrial systems at large, as well as of three tropical agrofuel systems, industrial plantations of eucalypts, acacias, and sugarcane.

At this stage, we can determine the degree of local unsustainability of U.S. maize production. We already know that external conversion of maize grain to ethanol is ca. 37% energy-efficient on the average, uses coal, natural gas, electricity and petroleum, and is therefore unsustainable, see Patzek (2006b, 2006a).

III. AVERAGE UNSUSTAINABILITY OF US MAIZE PRODUCTION

After a significant revision, see Appendices A–D, Svirezhev’s approach (2000) is applied to a productive agricultural maize system that has displaced (successionally closed) a fertile natural grassland system. In particular, the following function is used for the total entropy increment from a natural ecosystem (0) to an agrosystem (1)

\[
\frac{T}{A} \delta S \geq \frac{1}{A_0} (R_1 + \dot{D}_1 + \dot{W} + \dot{D}_{fc} - GPP_0) \quad [1]
\]

All the quantities appearing in this equation are explained below and in Appendices A–D.

Gross primary productivity of an agrosystem is \( GPP_1 \), expressed in energy units per area per time, here \( \text{GJ ha}^{-1} \text{yr}^{-1} \), see Patzek (2007) for details. Net primary productivity of this agrosystem is

\[
NPP_1 = GPP_1 - \dot{R}_1 = GPP_1 \left(1 - \frac{\dot{R}_1}{GPP_1}\right) = GPP_1 (1 - r) \quad [2]
\]

where \( R_1 \) is respiration rate by the agrosystem autotrophs and heterotrophs, mostly crop plants in maize fields, and \( r \) is the respiration ratio.

Crop yield \( \dot{Y} \) is a fraction \( k \) of the total crop biomass at the end of each year assumed to be the natural accounting period:

\[
\dot{Y} = k NPP_1 = k (1 - r) GPP_1 \quad [3]
\]

The remainder of plant biomass is transferred to the litter and soil, and decomposed within an accounting period:

\[
\dot{D}_1 = (1 - k)(1 - r) GPP_1 \quad [4]
\]

Note that consistently with Appendix D, if \( k = 0, \dot{D}_1 = NPP_1 \). If, in addition, \( \dot{W} = 0 \) and \( \dot{D}_{fc} = 0 \), \( GPP_1 = GPP_0 \) and \( \delta S = 0 \).

The average rates below are expressed per unit area of the agrosystem, and \( 1/A_0 \) is omitted:

\[
\begin{align*}
\dot{W} & \text{ Rate of anthropogenic energy inputs into the system} \\
\dot{D}_1 & \text{ Rate of energy production from crop biomass decomposition} \\
\dot{D}_{fc} & \text{ Rate of crop plant respiration} \\
GPP_0 & \text{ Rate of gross primary production of displaced ecosystem}
\end{align*}
\]

\[
\text{GJ ha}^{-1} \text{yr}^{-1} \quad [5]
\]

\( GPP_0 \) is the rate of solar energy dissipation in a successionally closed (displaced) natural ecosystem, equal to its gross primary productivity. \( \dot{W} \) is the rate of total anthropogenic exergy inputs, equal to the exergy in fertilizers, herbicides, pesticides, fossil fuels, electricity, etc. per year and hectare.

Fixing attention on a maize agrosystem in the U.S. Midwest, say, in North Dakota, Iowa or Nebraska, the displaced natural system was native grassland. A productive grassland may generate as much as 0.3 kg m\(^{-2}\) yr\(^{-1}\) of biomass above ground and 1.2 kg m\(^{-2}\) yr\(^{-1}\) below ground on dry mass basis (dmb) (Lauenroth and Whitman, 1977), or 15 tonnes of biomass dmb per hectare per year. With an average exergy of grass materials of 17 GJ (t dmb\(^{-1}\)) a native grassland may dissipate as much as 255 GJ ha\(^{-1}\) yr\(^{-1}\) of solar radiation by converting it to plant mass.

Let’s assume an average yield of maize to be 139 wet bushel acre\(^{-1}\) yr\(^{-1}\) of grain with 15 percent of moisture, and the exergy of 18 GJ (t dmb\(^{-1}\)), for a total of \( \dot{Y} = 134 \text{ GJ ha}^{-1} \text{yr}^{-1} \), see Appendix E for details. A logistic fit of average maize yield in the US, shown in Figure 4, is
FIG. 4. The best and an optimistic logistic fit of average U.S. maize yield in GJ ha$^{-1}$ yr$^{-1}$ or, approximately, bushel acre$^{-1}$ yr$^{-1}$. The maize yield data are from USDA-NASS. The optimistic ultimate maize yield for the U.S. is about 200 bushel acre$^{-1}$ yr$^{-1}$.

\[
\dot{Y} = \dot{Y}_0 + \frac{\dot{Y}_\infty - \dot{Y}_0}{1 + \exp[-r_c(t - t_c^*)]} \text{ GJ ha}^{-1} \text{yr}^{-1} \ [6]
\]

The logistic fit, due to Verhulst (1838), is also known as the Law of Diminishing Increment and the Law of the Soil, quantified in agriculture by Mitscherlich, Spillman, and Lang (1924). It may be argued (Loomis and Connor, 1992) that the single largest factor behind the 7-fold increase of maize yield over the last 100 years has been nitrogen fertilizer, followed by genetic gains, plant density, herbicides, and machinery. The decreasing factors have been less manure, less organic matter, erosion, insects, and crop rotations. It also follows that all easy genetic gains may have been already achieved with maize, as well as most other major crops. Therefore, Figure 4 may have a strong predictive capability.

The rate of anthropogenic inputs might follow a resource-limited policy

\[
\dot{W} = \frac{\dot{W}_\infty}{1 + \exp[-r_w(t - t_w^*)]} \text{ GJ ha}^{-1} \text{yr}^{-1} \ [7]
\]

that limits the maximum anthropogenic inputs at $\dot{W}_\infty$.

For sufficiently long time,$^9$ the exponential terms in Eqs. (6) and (7) become small compared with 1, and

\[
\eta \approx \frac{\dot{Y}_\infty}{\dot{W}_\infty} = \text{const} \ [8]
\]

Over the last four decades, efficiency of applying fertilizer to all grain crops has been constant in industrialized countries and has been declining in developing countries (Oerke et al., 1994; Cassman et al., 2003), see Figure 5. Therefore, for the industrialized countries, $\eta$ has been almost constant. The assumption of an almost constant $\eta$ is also satisfied when one calculates mass efficiency of applying elemental N, P, and K to maize in the U.S. over the last decade, see Figure 6. Roughly one-half of direct energy application to maize fields is related to N, P, K, and lime to deacidify soil damaged by excess of N fertilizer, see Appendix E. Most of the remainder of $\dot{W}$ is fossil fuels (diesel fuel, gasoline, natural gas, and coal) and electricity.

The intensity of use of electricity and natural gas depends on irrigation needs and amount of grain moisture to be removed, and may vary considerably from one year to another, see Patzek (2004). Diesel fuel saved on no-till agriculture is partially offset by an increased use of herbicides and pesticides (Benbrook, 2004), which contain 5–8 times more free energy per unit mass than diesel fuel and have to be sprayed by fossil fuel-powered machines. A massive application of pesticides, fungicides and herbicides has a disproportionately large effect on entropy generation by eliminating interspecies-communication and living organisms (destroying biological information), see Appendix F.

By analyzing soil data from the Morrow Plots,$^{10}$ the world’s oldest experimental site under continuous maize, Khan et al.

$^9$More than fifteen years after 1985 in Figure 4.

$^{10}$The Morrow Plots, which are located in the heart of the Urbana-Champaign campus of the University of Illinois, are the oldest continuous agricultural research fields in the United States. Established in 1876, they are predated only by the Rothamsted Field in England, which was started in 1843. The site was designated a National Historical Landmark by the federal government on Sept. 12, 1968.
FIG. 6. Efficiency of application of elemental N, P, K to U.S. maize in kg of grain dmb per kg of element applied. Note that N, P efficiencies are almost identical and constant over the last 10 years. The mean efficiency of elemental N is shown as the continuous line and ± one standard deviation as the dotted lines. The mean efficiency of elemental P is almost identical. Source: USDA NASS, accessed Nov. 11, 2007.

(2007) have found that intensive use of N fertilizers has decreased soil organic C (SOC) by 9–18 percent over 50 years. After 40 to 50 years of synthetic fertilization at levels that exceeded grain N removal by 60 to 190 percent, a net decline occurred in SOC despite increasingly massive incorporation of residue C. Their findings implicate fertilizer N in promoting the decomposition of crop residues and soil organic matter and are consistent with data from numerous cropping experiments involving synthetic N fertilization in the U.S. Maize Belt and elsewhere.

The average flux of direct anthropogenic energy dissipated in the US maize agriculture is \( W \approx 10.8 \text{ GJ ha}^{-1} \text{ yr}^{-1} \), see Appendix E, and \( \eta = 12.4 \). The ultimate \( \eta \) in Eq. (8) is approximated with this value.

Let’s denote

\[ \xi = k(1 - r) \]  

For maize, \( r \approx 0.45 \) and \( k \approx 0.5 \), and \( \xi \approx 0.3 \).

Equation (5) can now be rewritten as

\[ T \delta S \geq W + \frac{1 - \xi}{\xi} \dot{Y} + D_{fc} - GPP_0 \]

\[ \bar{T} \delta S \geq \bar{W} \left( 1 - \eta + \frac{\eta}{\xi} - 1 \right) + \bar{D}_{fc} - \bar{GPP}_0 \]

\[ \bar{T} \delta S \geq \bar{Y} \left( 1 + \frac{1}{\eta} - 1 \right) + \bar{D}_{fc} - \bar{GPP}_0 \]  

A. Calculations

The calculation results are tabulated in Appendix G for an average U.S. maize field and for the Lincoln, Nebraska, experimental field site. The parameter changing in both tables is the mass of mostly weeds killed by field chemicals. In U.S. maize agriculture, the mass of killed worms, beetles, larvae, fungi, viruses, etc. is almost negligible compared with the weeds, see (Oerke et al., 1994). All mass of eliminated life is assumed to decompose during the accounting period.

With the average values of parameters defined above, we get

\[ \bar{T} \delta S \geq 68 - 136 \text{ GJ ha}^{-1} \text{ yr}^{-1} \]  

\( \bar{T} \delta S \) is the excess energy dissipation by an agrofuel system over and above the energy dissipated by the displaced natural ecosystem. Under natural conditions, the latter energy would be transferred to the environment and radiated into space.

The ratio of the local restoration work in the average maize agrosystem, \( W_{rest} = \bar{T} \delta S \), to the anthropogenic inputs, \( W \), — the “unsustainability ratio” — is 6–13 times larger than the direct energy input to maize fields. This means that the work of nullifying the effects of anthropogenic energy inputs to intensive maize agriculture is 6–13 times larger than the direct energy input to maize fields. This work would have to be expanded on soil restoration, pollution control, etc., with no increase of crop yield.

The unsustainability ratio of the high-yielding (250 bushels per acre) irrigated maize in Lincoln, NE, is also higher, 13–17 times. Therefore, the “predicted” 300 bu/acre average maize yields on 90 million acres in the US would be even more unsustainable, were they not physically impossible. A 300 bu/acre maize yield corresponds to the upper limit of photosynthetic efficiency of maize plants, given perfect soil conditions, no weeds and pests, plentiful nutrients and water, and perfect weather (Lindquist et al., 2004).

B. Include the Environment?

As shown in Appendices A–D, the Earth (the maize field system + its environment) is a system closed to the flow of mass and open to the radiation of energy. Including the environment into the system increases further the already high irreversibility of maize fields. Take, for example, the neglected grain export from the fields. Assume that this grain is metabolized by animals and humans that do not die in a given year. Starch, fat, and proteins in the grain are ultimately converted into heat and radiated into space. But the grain also contains significant amounts of macronutrients, see Table 1, not to mention micronutrients. The entropy in the excreted grain macronutrients is \( \bar{T} \delta S_{grain} = 1.8 \text{ GJ ha}^{-1} \text{ yr}^{-1} \). Should the stover be exported as well, the entropy in its excreted macronutrients is another \( \bar{T} \delta S_{stover} = 1 \text{ GJ ha}^{-1} \text{ yr}^{-1} \).

In addition, all anthropogenic inputs to maize agriculture cause an irreversible consumption of exergy in the environment of maize fields. The cumulative exergy consumption related to \( W \) has been calculated by Patzek (2004). It is equal to \( CE_{ExC} = 40 \text{ GJ ha}^{-1} \text{ yr}^{-1} \), see Figure 45 there. Thus an increase of the


By Le Chatelier’s principle.
less entropy of the environment caused by maize agriculture is at
for a larger˙
ian maize agriculture when a steppe community (Hungarian
inputs (˙
) was obtained by Svirezhev (2000) for Hungar-
1 yr
1, depending on
The mean rate of soil production is
1860, and today has been appreciable, say 1/2 of topsoil has been
eroded, this critical yield must be less. Svirezhev (2000) calcu-
lates 2.9 t dbm ha
of 1 ton per hectare per year (McDaniel and Gowdy, 2000).
The mean erosion rate of conventional agriculture worldwide is
of 14 GJ ha
obtained by Bulatkin (1982) and
Novikov (1984). An even larger estimate of Wcrit = 16 GJ ha
yr
was obtained by Svirezhev (2000) for Hungarian maize agriculture when a steppe community (Hungarian “pusztas”) was a successional closed ecosystem. The reason for a larger Wcrit is that Svirezhev’s estimate of anthropogenic inputs (W = 27 GJ ha
yr
) is almost 3 times that for U.S. maize agriculture, see Appendix E.
The “limit energy load” concept of Bulatkin and Novikov is an empirical determination of the maximum total anthropogenic impact (including tillage, fertilization, irrigation, pest control, harvesting, grain transportation and drying, etc.) on 1 ha of a
The range of the Wcrit values for the Lincoln, Nebraska, site is identical.
The values of Wcrit calculated here are smaller than “the limit energy load” of 14 GJ ha
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) is almost 3 times that for U.S. maize agriculture, see Appendix E.

The “limit energy load” concept of Bulatkin and Novikov is an empirical determination of the maximum total anthropogenic impact (including tillage, fertilization, irrigation, pest control, harvesting, grain transportation and drying, etc.) on 1 ha of agricultural land per year. It is assumed that when the anthropogenic impact exceeds this limit, the agrosystem begins to deteriorate because of the destruction of soil flora and fauna, soil acidification and erosion, chemical contamination by Al, Fe, Se, herbicides and pesticides, etc. It turns out that the empirical “limit energy loads” for different maize agrosystems are somewhat higher than those calculated from the second law of thermodynamics. A similar observation was first made by Svirezhev (2000).

### D. The Limiting Crop Yield

The limiting (critical) yields at which the net rate of entropy export from the agrosystem is zero are

\[
\dot{Y}_{crit} \leq \frac{GPP_0 - \dot{D}_{fc}}{1 - \eta + \frac{\eta}{\zeta}} \approx 5.9 - 4.3 \ t \ dbm \ ha^{-1} \ yr^{-1}
\]

\[
= 7 - 5 \ t \ wet \ ha^{-1} \ yr^{-1}
\]

\[
\dot{Y}_{crit}
\]

for the Lincoln, Nebraska, site decreases from 7.2 to 5.3 t dbm ha
yr
, or from 8.5 to 6.2 t wet ha
yr
, depending on the mass of weeds and other life eliminated by field chemicals.

These values approximate the level of “sustainable” maize crops on the former prairie, i.e., the maximal crop production for sustainable agriculture, given the natural productivity of a successionaly closed “parent” ecosystem. If the cumulative soil erosion between the date of ploughing the natural prairie, say 1860, and today has been appreciable, say 1/2 of topsoil has been eroded, this critical yield must be less. Svirezhev (2000) calculates 2.9 t dbm ha
yr
for the Hungarian maize agriculture. In other words, the longer we wait to introduce sustainable agriculture, the lower yield threshold will be and the environmental cost goes up each year we repeat the same mistakes.

### IV. ECOSYSTEM DEGRADATION

Excess entropy generated in an agrosystem manifests itself mostly as soil degradation by chemical and mechanical means, and toxic effluent runoff. The leading mechanisms of soil erosion are flowing water, wind, and splashing rainwater. One should also account for the mechanical grinding of soil material by field machinery, the oxidation (slow burning) of soil organic matter (SOM), the buildup of toxic insoluble metal compounds (Al, Fe, Se, As, Cd, etc.), and the killing of soil bacteria and fungi by these metals and herbicides, as well as soil fauna by pesticides.

Over the past 150 years Iowa has lost 50 percent of its fertile topsoil to erosion, while the rate of loss was 30 tons per hectare per year in the 1990’s compared with a formation rate of 1 ton per hectare per year (McDaniel and Gowdy, 2000). The mean erosion rate of conventional agriculture worldwide is reported\(^{13}\) to be (Montgomery, 2007) 47 t ha
yr
while that of conservation (no till) agriculture that relies heavily of her-

\(^{13}\)using Montgomery’s value for the average bulk density of soil, 1200 kg m
.
of soil erosion on the average. The true local erosion rates may be several times higher across the Corn Belt.

Suppose that our fertile soil contains 4 percent of organic matter by weight and roughly 1/2 of this matter is of microbial origin (Simpson et al., 2007). The exergy of soil humus is about 19 MJ kg$^{-1}$, and the multiplication factor for bacterial biomass is roughly 3 (Jørgensen and Nielsen, 1998). Therefore, the total exergy of SOM in one metric ton of soil is

$$B_{SOM} \approx 20 \times 18.7 \times 10^6 + 3 \times 20 \times 18.7 \times 10^6 = 1.5 \text{ GJ (t soil)}^{-1}$$

This exergy is consumed by the oxidation of SOM.

The mechanical grinding of soil particles 1 mm in size to dust 1 µm in size involves 1.4 GJ (t soil$)^{-1}$ (Svirezhev, 2000). These dust particles are easily picked up by wind and washed out by water. Therefore the total exergy of soil destruction by agriculture is estimated as

$$\bar{T} \sigma_f = 1.5 + 1.4 \approx 3 \text{ GJ (t soil)}^{-1}$$

If the entire excess entropy of maize agriculture $\bar{T} \delta S$ went to soil destruction by these two mechanisms, the annual soil erosion rate would be

$$m_s = \frac{\bar{T} \delta S}{\bar{T} \sigma_f} \geq 23 - 45 \text{ t ha}^{-1} \text{yr}^{-1}$$

for U.S. maize agriculture on the average, and 74–97 t ha$^{-1}$ yr$^{-1}$ for the Lincoln, Nebraska, site.

These calculated soil erosion rates range from the recent higher estimate of soil erosion in midwest (23 t ha$^{-1}$ yr$^{-1}$) to the mean rate of soil erosion in conventional agriculture calculated by Montgomery (2007) from his analysis of 448 field sites (47 t ha$^{-1}$ yr$^{-1}$).

Many have high hopes for “conservation,” no-till agriculture. This agriculture gets rid of much of $\bar{T} \sigma_f$ by eliminating most of soil grinding, and avoiding the exposure of barren soil to wind and water. Montgomery has found that the mean erosion rate for no-till agriculture is only 1.5 t ha$^{-1}$ yr$^{-1}$, so what happens to the excess entropy equivalent to oxidizing and eroding a soil quantity of 45.4 - 1.5 ≈ 44 t ha$^{-1}$ yr$^{-1}$? The second law of thermodynamics allows no exceptions. Therefore the entropy of mechanical soil grinding and oxidation must be replaced with the entropy of chemical degradation of soil by killing off its flora and fauna, and by chemical contamination.

During the last 50 years, microbiology has shown that life processes taking place in soil were larger and deeper than it had been assumed earlier (Krasil’nikov, 1958). Whereas in the 1950s, hundreds of thousands and millions of microbial cells were counted in one gram of soil, more recently, with more improved methods of investigation, hundreds of millions and billions were determined. The total bacterial mass in the top 15 cm of the surface layer of one hectare of fertile land is 0.5–5 tons, and the masses of actinomycetes and fungi are 0.5–5 and 1–15 tons, respectively (Brady and Weil, 2004).

No less important is the soil fauna. According to different authors, amoebae, ciliata, and other protozoa are numbered in tens and hundreds of thousands in one gram (Brodkii, 1935; Nikolyuk, 1949; Dogeli, 1951). In one square meter of the surface layer of soil some tens to hundreds of larger invertebrates may be found—earth worms, myriapods, larvae of various beetles, etc. The population of small non-microscopic arthropods (ticks, Collembola, and others) is numbered in tens and hundreds of thousands in 1 m$^2$ of cultivated soil layer, and in forest soils their number often amounts to a million individuals. The number of nematodes is sometimes counted in millions per 1 m$^2$. According to the counts of Gilyarov (1953), the total mass of this fauna comprises several tons (3–4) per hectare of soil.

Jørgensen and Nielsen (1998) calculate the multiplication factors of bacteria and worms to be 3 and 35, respectively, relative to the detritus exergy of 18.7 MJ kg$^{-1}$. So, if equal proportions of bacteria and soil fauna are killed by the herbicides, pesticides and buildup of toxic metals in soil, it is sufficient to kill

$$m_{life} = \frac{136200 \times 44}{(3 + \frac{3}{5} \times 35) \times 18.7} \approx 300 \text{ kg ha}^{-1} \text{yr}^{-1}$$

Thus, killing off with field chemicals just 300 kilograms of bacteria and worms per hectare per year (roughly 4 percent per year of the initial soil flora and fauna) will do the job. Of course, difficulties then arise with nitrogen sequestration by plants (Fox et al., 2007), nutrient mineralization, and general health of soil. In short, weeds become herbicide-resistant and pests pesticide-resistant, and more field chemicals must be applied each year, killing more soil life (Benbrook, 2004; May, 1985). Recall that according to Kutsch et al. (1998), maize monoculture fields showed non-detect soil fauna with their measurement methods.

V. SUMMARY AND CONCLUSIONS

It has been shown that a productive industrial maize agricultural system that has successsionally closed a fertile prairie ecosystem is unsustainable, with or without tilling the soil. Its degree of unsustainability is high, requiring at least 6–13 times more energy to remediate soil degradation, etc., than the direct energy inputs to maize agriculture. The calculated average erosion rate of soil necessary to dissipate the entropy produced by U.S. maize agriculture, 23–45 t ha$^{-1}$ yr$^{-1}$, is bounded by an experimental estimate of mean soil erosion by conventional agriculture (Montgomery, 2007) worldwide, 47 t ha$^{-1}$ yr$^{-1}$. The much lower mean erosion of no till agriculture, 1.5 t ha$^{-1}$ yr$^{-1}$, necessitates chemical and biological soil degradation to dissipate the produced entropy. The increased rate of use of field chemicals to replace tilling may require the killing and otherwise weakening of up to 300 kg ha$^{-1}$ yr$^{-1}$ of soil flora and fauna.
Additional soil degradation occurs by acidification, buildup of insoluble metal compounds, and buildup of toxic residues from field chemicals. Some of the entropy generated in maize fields is exported as toxic runoff of surface and ground water, and flows all the way to the Gulf of Mexico, thus causing eutrophication of remote ecosystems embedded in the environment of the agrosystem. More of the entropy generated by maize fields is exported to the atmosphere as ammonia NH₃, nitrous oxide N₂O, carbon oxides CO₂ and CO, methane CH₄, and vapors of field chemicals (Patzek, 2006b; Crutzen et al., 2007; Yao et al., 2007).

The maximum allowed yield of "organic" maize agriculture is 6.7 t wet ha⁻¹ yr⁻¹ vs. 8.7 t wet ha⁻¹ yr⁻¹ for U.S. industrial maize agriculture in 2005, provided that no field chemicals are used to eradicate the weeds. With 2000 kg of eradicated weeds per hectare, this yield is 6 t wet ha⁻¹ yr⁻¹. At this "critical yield," organic agriculture generates as much entropy as the displaced and closed native prairie system and, if this entropy does not come from field chemicals and fossil fuels, it can be radiated into space. By this criterion the "organic" maize agriculture would be sustainable. Therefore, any attempt to arrive at a sustainable agriculture would have to rely on the solar energy to drive electric field machinery (Patzek, 2007), on the maximum possible recycling of biomass, and on the preservation of biodiversity of the soil and of the multi-species, preferentially, perennial crops (Jackson, 1980). We are a long way from this ideal, but learning from the phenomenal scientific trip diary by King (1911) and the ground-breaking work of Jackson’s Land Institute might be a good start. From a detailed analysis of an organic farm by Baum et al. (2008), it also follows that the sustainable smaller farms would have to be inter-dispersed with small towns to limit transportation fuel use, which otherwise nullifies sustainability.

VI. ACKNOWLEDGMENTS

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THERMODYNAMICS OF AGRICULTURAL SUSTAINABILITY

APPENDICES

A. MASS BALANCE

Appendices A–D draw heavily on the epochal monograph by de Groot and Mazur (1962). Materials from six different courses the author has taught at U.C. Berkeley have also been used. These courses deal with the flow of energy, solids, and fluids in earth systems at different time- and spacial scales.

The “system” is a fixed region of space separated from the “environment” by a curvilinear “pillbox” that is offset from ground surface by slightly more than the height of the tallest living organism, and extends at least 1 meter below soil surface and below lake, river and swamp beds. The box walls are permeable to radiation, heat conduction and convection, wind, water, chemicals, living creatures, and machines. As pointed out by Dr. Chapella, one has to be careful in specifying the spacial and temporal scales of the thermodynamic arguments below. The temporal scale has been addressed by Patzek (2007) elsewhere. It seems that the annual cycles of natural ecosystems should be averaged over decades or more. Some of the agrosystems that close natural ecosystems may not persist long enough to ever become steady-state. As to the spacial scale, this analysis can be applied to state-wide agriculture on, say, a county or farm level. A typical system boundary might encompass an area of 10–1000 hectares, see Figure 7.

Because the system-environment interface $A_{se}$ that bounds the system volume $V_s$ does not move relative to the Earth, one can write the following mass balance for each of the $n$ chemical components (not necessarily chemical species) crossing it and/or produced in the system interior by chemical reactions:

$$
\int_{V_s} \frac{\partial \rho_k}{\partial t} dV = -\int_{A_{se}} \rho_k v_k \cdot n \, dA + \int_{V_s} \sum_{j=1}^{r} v_{kj} r_j \, dV
$$

$$
\text{kg yr}^{-1}, \quad k = 1, 2, \ldots, n
$$

[18]

Here $\rho_k$ is the mass density (mass/volume) of component $k$; $v_k$ is the velocity of $k$; $n$ is the unit outside normal to the boundary surface $A_{se}$; and $v_{kj} r_j$ is the rate of production of $k$ per unit volume in the $j$th chemical reaction. The quantity $v_{kj}/M_k$ is proportional to the stoichiometric coefficient of $k$ in reaction $j$, $M_k$ being the molecular weight of $k$.

The volume-averaged quantities $\rho_k$, $v_k$, and $r_j$ are all functions of time and space coordinates. Assumptions underlying the mechanics and validity of volume averaging will be elucidated in a separate paper.

Applying the Green-Gauss-Ostrogradskii (GGO) theorem to the surface integral in Eq. (18) we get

$$
\frac{\partial \rho_k}{\partial t} = -\nabla \cdot (\rho_k v_k) + \sum_{j=1}^{r} v_{kj} r_j, \quad k = 1, 2, \ldots, n
$$

[19]

because (18) is valid for an arbitrary volume $V_s$.

FIG. 7. A typical agricultural system may be bounded by a “pillbox” whose side walls follow the roads that surround the fields. A “lid” of the box might be 1 m above the tree tops, and its bottom 1 m below the ground surface. Source: T. W. Patzek, aerial view of fields near Salina, Kansas, June 14, 2007.
Since mass is conserved in each chemical reaction,
\[ \sum_{k=1}^{n} v_{kj} = 0 \quad j = 1, 2, \ldots, r \]  \[20\]
we can sum Eq. (19) over all components and obtain the overall law of mass conservation for the system:
\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) \]  \[21\]
where \( \rho \) is the total density:
\[ \rho = \sum_{k=1}^{n} \rho_k \]  \[22\]
and \( \mathbf{v} \) is the center of mass or “barycentric” velocity:
\[ \mathbf{v} = \sum_{k=1}^{n} \rho_k \mathbf{v}_k / \rho \]  \[23\]
The mass balance equations can be written in an alternative form by introducing the barycentric convective (Lagrangian) derivative
\[ \frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \]  \[24\]
and the diffusion flux of \( k \)
\[ j_k = \rho_k (\mathbf{v}_k - \mathbf{v}) \]  \[25\]
With the help of Eqs. (24) and (25), Eqs. (19) become
\[ \frac{d \rho_k}{dt} = -\rho_k \nabla \cdot \mathbf{v} - \nabla \cdot j_k + \sum_{j=1}^{r} v_{kj} j_j, \quad k = 1, 2, \ldots, n \]  \[26\]
and Eq. (21) becomes
\[ \frac{d \rho}{dt} = -\rho \nabla \cdot \mathbf{v} \]
\[ \frac{d \mathbf{v}}{dt} = \delta \nabla \cdot \mathbf{v} \]  \[27\]
where \( \dot{\nu} \equiv \rho^{-1} \) is the specific total volume.
We can introduce the component mass fractions
\[ c_k = \rho_k / \rho, \quad \sum_{k=1}^{n} c_k = 1 \]  \[28\]
and, using Eq. (27), rewrite Eqs. (19) as
\[ \rho \frac{dc_k}{dt} = -\nabla \cdot j_k + \sum_{j=1}^{r} v_{kj} j_j, \quad k = 1, 2, \ldots, n \]  \[29\]
Note that the diffusion fluxes sum to zero, i.e., only \( n - 1 \) of them is independent.
It turns out\(^{14}\) that for a quantity \( \Psi \) of any tensorial rank
\[ \rho \frac{d \Psi}{dt} = \frac{\partial (\rho \Psi)}{\partial t} + \nabla \cdot (\rho \mathbf{v} \Psi) \]  \[30\]
B. MOMENTUM BALANCE
In a similar manner, the equations of motion of a material particle can be obtained from the principle of momentum conservation and the GGO theorem applied to the contact forces acting across the interface:
\[ \rho \frac{d \mathbf{v}}{dt} = -\nabla \cdot \mathbf{P} + \sum_{k=1}^{n} \rho_k \mathbf{F}_k \quad \text{N m}^{-3} \]  \[31\]
where \( \mathbf{P} \) is the (surface) stress tensor, and \( \mathbf{F}_k \) is the (volumetric) body force acting on \( k \):
\[ \mathbf{F}_k = -\nabla \psi_k, \quad \frac{\partial \psi_k}{\partial t} = 0 \]  \[32\]
using Eqs. (27) and (29), the equation of motion (31) can be recast into the following form:
\[ \frac{\partial \rho \mathbf{v}}{\partial t} = -\nabla \cdot (\rho \mathbf{v} \mathbf{v} + \mathbf{P}) + \sum_{k=1}^{n} \rho_k \mathbf{F}_k \quad \text{N m}^{-3} \]  \[33\]
where \( \mathbf{vv} \) is a bivector or dyad (Gibbs, 1994), and \( \rho \mathbf{v} \) is the momentum density. By taking the dot product of Eq. (33) with \( \mathbf{v} \), inserting Eq. (32), and some rearrangement one gets the balance equation for the kinetic plus potential energy:
\[ \frac{\partial (\frac{1}{2} \rho \mathbf{v}^2 + \psi)}{\partial t} = -\nabla \cdot \left[ \rho \left( \frac{1}{2} \mathbf{v}^2 + \psi \right) \mathbf{v} + \mathbf{P} \cdot \mathbf{v} - \sum_{k=1}^{n} \psi_k j_k \right] \]
\[ + \mathbf{P} : \mathbf{v} - \sum_{k=1}^{n} j_k \cdot \mathbf{F}_k \]  \[34\]
The source term due to irreversible viscous dissipation and diffusion
Note that the sum of kinetic and potential energy of a multicomponent material particle is destroyed by friction and diffusion as its center of mass moves in space.
C. ENERGY BALANCE
Total energy is conserved for each material particle. The total specific energy is the sum of internal energy, \( u \), kinetic energy,
\[ v^2/2, \text{ and potential energy, } \psi: \]
\[ e = u + \frac{1}{2} v^2 + \psi \quad \text{MJ kg}^{-1} \]  

The conservation equation is
\[ \int_{V_i} \frac{\partial \rho e}{\partial t} \, dV = -\oint_{A_e} j_e \cdot n \, dA \quad \text{MJ s}^{-1} \]

or, after the usual steps,
\[ \frac{\partial \rho e}{\partial t} = -\nabla \cdot j_e \quad \text{MJ s}^{-1} \text{ m}^{-3} \]  

where the rate of heat addition to a material particle is defined as
\[ \rho \frac{d\theta}{dt} := -\nabla \cdot j_q \quad \text{MJ s}^{-1} \text{ m}^{-3} \]  

and \[ \mathbf{I} : \nabla \nabla = \mathbf{I} \cdot \nabla \cdot \nabla. \]

With the use of Eq. (27), Eq. (41), the first law of thermodynamics for a multicomponent fluid particle that exchanges mass and heat with its environment is
\[ \frac{du}{dt} = \frac{dq}{dt} - \rho \frac{d\phi}{dt} - \dot{\theta} \mathbf{I} : \nabla \nabla + \dot{\theta} \sum_{k=1}^{n} j_k \cdot F_k \]  

D. ENTROPY BALANCE

The system and/or the environment satisfy the following assumptions:

1. An agrosystem successively closes a mature metastable ecosystem, replacing it with agricultural fields in a state of "perpetuated succession."
2. The eco/agrosystem ("the system") is open to flow of mass and heat.
3. The rest of the planet ("the environment") and the system together are closed to mass flow.
4. The environment radiates heat into the universe.
5. The successively closed mature ecosystem is assumed to have exported mostly heat into the environment.

Assumption 1 does not quite hold for the U.S. agriculture in 2007, when the prairie system was closed by 1900. For example, soil organic carbon (SOC) typically has been reduced 30 to 50% of precultivation levels (Schlesinger, 1985) through crop production activities. Therefore, if one accounts for the subsequent degradation of soil by the first 100–150 years of agriculture, then the reference gross primary productivity, GPP0, would have to be smaller, and the current agrosystem even more unsustainable.

Assumption 4 is validated by the thermodynamics of the planet Earth (see Patzek, 2007; Ponting, 2007), and Figure 1. The Earth is the sum of the System and the Environment in Figure 8.
The balance of the rate of total entropy change on the Earth that consists of the system (s) and the environment (e) is

$$\frac{dS}{dt} = \frac{dS_s}{dt} + \frac{dS_e}{dt}, \quad \text{J} \text{K}^{-1} \text{yr}^{-1} \quad [44]$$

where the increment of entropy of the system consists of two parts, the entropy produced inside the system (i) and the entropy supplied to the system by its environment (e):

$$dS_s = dS_{s,i} + dS_{s,e} \quad \text{J} \text{K}^{-1} \text{yr}^{-1}$$

$$dS_{s,i} \geq 0, \quad dS_{s,e} \leq 0 \quad [45]$$

Similarly the increment of entropy of the environment is

$$dS_e = dS_{e,i} + dS_{e,s} + dS_{e,r} \quad \text{J} \text{K}^{-1} \text{yr}^{-1}$$

$$dS_{e,i} \geq 0, \quad dS_{e,s} = 0$$

$$dS_{e,r} = -dS_{e,e}$$

$$dS_{e,r} \approx \frac{Q_e}{T} \left( \frac{1366 \ 300}{235 \ 6000} - 1 \right) = -0.9 \frac{Q_e}{T} < 0 \quad [46]$$

where $dS_{e,r}$ is the negative net supply of radiation entropy to the Earth.$^{16}$

For the closed Earth, a well-known Carnot-Clausius statement of the second law of thermodynamics is

$$\frac{dS}{dt} = \frac{dS_{t,i}}{dt} + \frac{dS_{e,i}}{dt} + \frac{Q_{\text{sun}}}{T_{\text{sun}}} - \frac{Q_e}{T} \quad [47]$$

For a steady-state Earth, over a sufficiently long time interval that is not too long, however (Barenblatt, 1994), it is reasonable to assume that

$$\frac{dS}{dt} \approx 0$$

Remark 1 Given sufficient time, entropy generated inside a natural ecosystem is close to the net reduced heat exported into the universe via the environment. Because of this constraint, natural ecosystems must recycle almost all mass. One species waste is another species food and there can be no “trash” (Patzek, 2007).

For a large spatially-distributed system and its environment we assume (De Groot and Mazur, 1962) that entropy and mass can be suitably described by their densities that are continuous function of space and time:

$$S_i = \int_{V_i} \rho_s dV, \quad i = s, e \quad [49]$$

where $\rho$ is the total mass density, $s$ is the total entropy per unit mass, and $V_i, i = s, e$, is the volume of the system or the environment.

The rate of entropy production by the system is

$$\frac{dS_{s,i}}{dt} = \int_{V_s} \sigma dV \quad [50]$$

where $\sigma$ is the entropy source strength or entropy production per unit volume and unit time.

The rate of entropy supplied by the environment is

$$\frac{dS_{s,e}}{dt} = -\oint_{A_e} n_{s,tot} \cdot dA \quad [51]$$

where $n_{s,tot}$ is the vector of total entropy flow per unit area and unit time (the mass-fraction based entropy flux), through the system-environment interface $A_e$ oriented by the outside unit normal from the system into the environment.

Thus, the entropy balance of the system is

$$\int_{V_s} \frac{dS_s}{dt} dV = -\oint_{A_e} n_{s,tot} \cdot dA + \int_{V_s} \sigma dV \quad [52]$$

Rate of entropy accumulation Net entropy inflow $\Xi_s = \text{Rate of entropy production}$

In steady state or quasi-steady state, the accumulation term is zero or negligible, and

$$\Xi_s = \oint_{A_e} n_{s,tot} \cdot dA \quad [53]$$
Let us define

\[ \dot{\mathbf{j}}_k = n_{s,tot} - \rho s v \]

\[ v = \sum_{k=1}^{n} c_k v_k \]  

[54]

where \( v \) is the center-of-mass or “barycentric” velocity of mass flow, \( \rho = \sum_k \rho_k \) is the total density of material “particles,” and \( c_k \) are the overall mass fractions of the \( n \) components of the system.

Using the mass-continuity equation and the divergence theorem, we may rewrite Eq. (52) as

\[ \int_{V_s} \left( \rho \frac{ds}{dt} + \nabla \cdot \dot{\mathbf{j}}_{s,tot} - \sigma \right) dV = 0 \]  

[55]

or, because \( V_s \) is an arbitrary volume, the differential entropy balance equation is obtained at each point of the system’s volume:

\[ \rho \frac{ds}{dt} = -\nabla \cdot \dot{\mathbf{j}}_{s,tot} + \sigma, \quad \sigma \geq 0 \]  

[56]

In other words, we have assumed that the macroscopic laws of thermodynamics (44) also hold for very small volumes, or mathematical “points” in \( V_s \). These “points” are obtained through volume averaging procedures that will be addressed in a separate paper.

Now we must relate the quantities appearing in Eq. (56) to the more directly measurable variables. To do so, we first assume that the specific entropy, energy, volume and overall composition are related by the standard thermodynamic equilibrium relationship:

\[ T d s = d u + p d v - \sum_{k=1}^{n} \mu_k d c_k \]  

[57]

where \( u \) is the specific internal energy, \( \mu_k \) the chemical potential of component \( k \), \( v = 1/\rho \) is the total specific volume. After de Groot and Mazur (1962), We also assume that

\[ \rho \frac{ds}{dt} = \rho \frac{du}{T \frac{dt}{d\rho}} + \rho \frac{p}{T} \frac{dv}{d\rho} - \rho \sum_{k=1}^{n} \mu_k \frac{dc_k}{d\rho} \]  

[58]

where the time derivatives are convective or Lagrangian, i.e., they follow material “particles” moving with the center-of-mass velocity. Validity of Eq. (58) is rather uncertain and its limitations will be established in a separate paper.

By inserting the standard equations of thermodynamics (42), (43), (27), and (29) into the formula (58), and rearrangement, it can be shown that

\[ \rho \frac{ds}{dt} = -\nabla \cdot \left( \frac{\dot{\mathbf{j}}}{T} + \sum_{k=1}^{n} \frac{\mu_k}{T} (-\dot{\mathbf{j}}_k) \right) \]

The divergence of the “reduced heat” flux \( in \) and the “reduced free energy” diffusion fluxes \( out \)

\[ -\frac{1}{T} \sum_{k=1}^{n} \dot{\mathbf{j}}_k \cdot T \nabla \frac{\mu_k}{T} - F_k \]

\[ + \nabla \mathbf{v} + \sum_{j=1}^{r} r_j A_j \]  

[59]

where the entropy production term consists of four parts:

\[ \sigma T = -\left[ \left( \frac{\dot{\mathbf{j}}}{T} \cdot \nabla T + \sum_{k=1}^{n} \dot{\mathbf{j}}_k \cdot \left( T \nabla \frac{\mu_k}{T} - F_k \right) \right) \right] \]

Heat

Conduction flux

Mass diffusion fluxes

\[ + \mathbf{P} : \nabla \mathbf{v} + \sum_{j=1}^{r} r_j A_j \]  

\[ \geq 0 \]  

[60]

\( F_k \) is the body force (here gravity) acting on component \( k \), \( \mathbf{P} \) is the shear stress tensor in a fluid, and

\[ A_j = \sum_{k=1}^{n} v_{kj} \mu_k \]  

[61]

is the affinity of chemical reaction \( j \leq r \), whose kinetic rate is \( r_j \).

Now we can return to the Eulerian description and simplify the resulting equation by assuming that the divergence of the total barycentric velocity \( \nabla \cdot v \approx 0 \), i.e., the total material “particles” are almost incompressible. Then the total specific entropy convection term is

\[ \rho v \cdot \nabla s = \rho v \cdot \nabla \sum_{k=1}^{n} \frac{c_k (h_k - \mu_k)}{T} \approx \nabla \cdot (\rho v s) \]

\[ = \nabla \cdot \left( \rho v \sum_{k=1}^{n} \frac{c_k (h_k - \mu_k)}{T} \right) \]  

[62]
where $h_k$ is the specific enthalpy of component $k$. Now Eq. (59) becomes

$$
\frac{\partial \rho s}{\partial t} \approx -\nabla \cdot \left[ j_k \frac{T}{T} + \left( \sum_{k=1}^{n} \frac{\mu_k}{T} - j_k \right) \right] + \left( \rho v \sum_{k=1}^{n} c_k (h_k - \mu_k) \right) + \sigma \tag{63}
$$

Equation (62) can be integrated over the system volume and time-averaged over an accounting period $\Delta t$, usually one year:

$$
\frac{S_v(t + \Delta t) - S_v(t)}{\Delta t} = \langle S_v \rangle = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} \left( \int_{V_v} \frac{\partial \rho s}{\partial t} \, dV \right) \, dt \approx -\frac{1}{\Delta t} \int_{t}^{t+\Delta t} \left\{ \left( \int_{A_v} \nabla \cdot j_k \frac{T}{T} \, dA + \rho v \sum_{k=1}^{n} c_k (h_k - \mu_k) \right) \cdot dA \right\} \, dt + \frac{1}{\Delta t} \int_{t}^{t+\Delta t} \left( \int_{V_v} \sigma \, dV \right) \, dt \tag{64}
$$

Finally, the time-averaged total entropy balance of the system is:

$$
\langle S_v \rangle \approx \left( \frac{Q_{in}}{T} - \frac{\mu_{diff, out}}{T} + S_{conv, in} \right)_{\text{net}} + \langle \Xi_s \rangle \tag{65}
$$

usually this balance is calculated per unit surface area of the system, $A_s$, measured in e.g. hectares, and multiplied by an average system temperature, $T$. The units are then GJ yr$^{-1}$ ha$^{-1}$:

$$
\frac{T}{A_s} \langle S_v \rangle \approx \frac{T}{A_s} \left( \frac{Q_{in}}{T} - \frac{\mu_{diff, out}}{T} + S_{conv, in} \right)_{\text{net}} + \frac{T}{A_s} \langle \Xi_s \rangle \tag{66}
$$

Even though Eq. (65) was obtained from the assumption of “closeness” to a thermodynamic equilibrium, its general form is valid for all systems if we replace the equal sign with “$\geq$”, see (De Groot and Mazur, 1962; Hatsopoulos and Keenan, 1965). In other words, the true entropy increment is bounded from below by the right-hand side of Eq. (65).

Let U.S. analyze the two right-hand side terms in Eq. (65). The first term in the brackets is the time-averaged net inflow rate of entropy across the system boundary:

1. $\langle Q_{in}/T \rangle$ is the net rate of inflow of reduced heat from the solar radiation reaching the system through the environment, respiring organisms and the system surfaces, and the heat of exchange through mass-impermeable membranes (zero, unless cooling lava flow tubes or geothermal vents are present).

2. $\langle \mu_{diff, out}/T \rangle$ is the net rate of diffusion of reduced free energy. Compared with the other two terms, this term is usually very small in ecosystems and will be neglected.

3. $\langle S_{conv, in} \rangle$ is the net inflow rate of total entropy convected into and out of the system with rain, evapotranspiration, rivers and streams; waterborne soil erosion and airborne soil dust; airborne gases produced in the system (methane, ammonia, nitrous and sulfur oxides, herbicide and pesticide vapors, etc.); crop transport out of the system; fossil fuel, fertilizer, lime, field chemical, etc. transport into the system; animals, birds, insects, people and machines crossing the system boundary; etc.

The time-averaged total entropy production rate term, $\langle \Xi_s \rangle$ has two main components, cf. Eq. (60), because heat conduction and friction are usually negligible in ecosystems, unless molten lava flows, geothermal processes, or fast flowing rivers dominate. These two components describe the diffusion of nutrients and the associated metabolic reaction rates, plant and animal decomposition, as well as chemical reactions of soil oxidation, fossil fuel burning and chemical decomposition of fertilizers and field chemicals. The field chemicals also kill life in the ecosystem, bacteria, fungi, non-crop plants, soil worms and animals, and all these processes generate entropy:

1. The rate of entropy production by nutrient diffusion and metabolism has been described by Virgo & Harvey (2007). Here it will be approximated by the time-averaged net rate of plant respiration, $\dot{R}_a/T$.

2. The net inflow rate and the rate of entropy generation by anthropogenic energy inputs to the system will be approximated by the total exergy of these inputs dissipated into heat at the average system temperature. Thus the time-averaged anthropogenic entropy flows and sources input will be approximated as

$$
\frac{W}{T} = \sum_{i} \frac{m_i b_i}{T} \tag{67}
$$

where $b_i$ denotes the specific exergy with the mass flow rate, $m_i$, of input $i$, see Appendix E.

3. The rate of entropy generation from the decomposition of weeds and other life killed by field chemicals is $\dot{D}_f/T$. The action of field chemicals is discussed in Appendix F.

4. The rate of entropy generation by biomass decomposition will be approximated by the exergy of plant litter and root decomposition divided by the average system temperature, $D/T$. If crop mass is equal zero and $D_f = 0$, then $\dot{D} \approx GPP - \dot{R}_a = NPP$.

5. The excess entropy production and transport by the anthropogenic soil erosion, life extermination, and chemical contaminant effluents will be captured by subtracting the exergy of gross primary productivity of the successively closed ecosystem that in a steady state must recycle most of its mass and radiate only heat, $GPP_0/T$.
In summary, to describe the irreversible U.S. maize agriculture, we consider the following increment of the rate of entropy accumulation for an agrosystem:

\[
\dot{\bar{T}}_{\text{a}} \delta S \geq \frac{1}{A_x} (\dot{R}_a + \dot{D} + \dot{W} + \dot{D}_{f,c} - \dot{GPP}_0) \quad [68]
\]

This entropy increment captures the main flow rates and production mechanisms of non-radiation entropy in the system over and above the successively closed natural ecosystem. If an agrosystem were the original ecosystem, then \( \dot{W} = 0, \dot{D}_{f,c} = 0 \), see Appendix VI., \( \dot{R}_a + \dot{D} \approx \dot{GPP}_0 \), and \( \delta S \approx 0 \), as required. \( \delta S \) is, however, neither a pure rate of entropy production, as implied by Svirezhev (1998, 2000) and many others, who reprinted Svirezhev’s results in their papers and books, nor a pure entropy flow rate. It is a sum of most of both contributions, minus an estimate of the rate of total entropy production by autotrophs in the displaced ecosystem. Several potentially important contributions from contaminant flows into the environment and the system’s soil contamination have been omitted at this time.

Remark 2 More work needs to be done to sharpen the incremental entropy balance sketched here. Among others, issues with time and volume averaging of the entropy balance, the zero divergence of the barycentric velocity, and with the large departures from equilibrium must be fully addressed.

E. ENERGY OF ANTHROPOGENIC INPUTS

The total exergy of direct anthropogenic inputs to U.S. maize agriculture is based on a USDA estimate of average mass flows, see Table 2. The specific exergy, \( b \), of each input is taken from Tables 5.1 and 5.2 in Szargut et al. (1988), Patzek (2004a), or calculated using an exergy calculator at the Exergoecology portal. The cumulative energy consumption (CExC) by the exterior processes utilized to obtain these inputs has been ignored, because the system here is limited only to agricultural fields. Note that Svirezhev, 2000, and Svirezhev et al. (2000), inconsistently add to their anthropogenic inputs the energy costs of transportation and manufacturing of field machinery. Also their energy in N fertilizer is much too high because it involves the cumulative energy consumption in the fertilizer production. These additional energy costs are borne by the environment of the fields and should not be included in the systems bounded by the field boundaries. A different analysis elsewhere allows for the inclusion of these costs, see Patzek (2004). Consequently, the anthropogenic energy inputs to maize agriculture by Svirezhev et al. are significantly higher (27, 97, and 37 GJ ha\(^{-1}\) yr\(^{-1}\)) than the exergy fluxes listed in Tables 2 and 3 (11 and 17 GJ ha\(^{-1}\) yr\(^{-1}\)).

Another estimate of anthropogenic energy inputs is for the experimental site of the University of Nebraska in Lincoln, Nebraska, (Dobermann et al., 2005) see Table 3. The significantly higher maize yield in Nebraska is achieved with higher direct inputs, 16.7 vs. 10.8 GJ ha\(^{-1}\) yr\(^{-1}\), and ample irrigation. Also, the maize grain fraction, \( k = 0.57 \), can be calculated directly for the Nebraska site and, assuming \( r \approx 0.4, \xi = 0.34 \) vs. \( \xi \approx 0.3 \) assumed for U.S. maize agriculture.

F. ENTROPY GENERATION BY FIELD CHEMICALS

Maize yield decreases, at times to zero, because of maize plant susceptibility to weeds, pathogens (bacteria, fungi, and
The Nobel Prize in Physiology and Medicine for his discovery of the insecticidal prowess of DDT.

The new pesticides and/or their metabolic products can persist in the environment for a long time and remain toxic to life (Robinson, 1970). Ultimately the pesticide and its metabolic products are degraded by metabolic, photochemical, oxidative and hydrolytic processes (Gunther, 1969). The stories of herbicides and fungicides are not dissimilar. Atrazine (2-chloro-4-ethylamine)-6-(isopropylamine)-s-triazine) is the most heavily used herbicide in the United States. It may be applied both before and after planting to control broadleaf and grassy weeds. Approximately 35 000 metric tons of active ingredient are applied in the U.S. per year.19 Its primary uses are maize and corn-soybean systems. Approximately 90% of Midwest U.S. corn is treated with atrazine. Farms and farmland have been responsible for almost all runoff of pesticides, fungicides, and herbicides measured in the United States. Between 1980 and 2000, the area treated each year with atrazine more than doubled. Atrazine is the most heavily used pesticide in the United States. Annual applications of atrazine in the United States range from about 35 000 to 70 000 metric tons (a 50% increase in the last 20 years).

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18 The Swiss scientist Paul Hermann Müller was awarded the 1948 Nobel Prize in Physiology and Medicine for his discovery of the insecticidal prowess of DDT.
Entropy generation by field chemicals can be deduced as follows. For simplicity, we assume that these chemicals remain in the system until they are decomposed. Otherwise, the chemicals and their metabolic products flow out of the system, kill life in the environment, and generate a similar amount of entropy.

### TABLE 4
Results of calculation of entropy generation by U.S. maize agriculture

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Values</th>
<th>Values</th>
<th>Values</th>
<th>Values</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^a$</td>
<td>10.8</td>
<td>10.8</td>
<td>10.8</td>
<td>10.8</td>
<td>10.8</td>
</tr>
<tr>
<td>$\dot{Y}^a$</td>
<td>133.9</td>
<td>133.9</td>
<td>133.9</td>
<td>133.9</td>
<td>133.9</td>
</tr>
<tr>
<td>$\dot{m}_{life}^{b,c}$</td>
<td>0.0</td>
<td>1000.0</td>
<td>2000.0</td>
<td>3000.0</td>
<td>4000.0</td>
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<tr>
<td>$D_{fc}^a$</td>
<td>0.0</td>
<td>17.0</td>
<td>34.0</td>
<td>12.4</td>
<td>12.4</td>
</tr>
<tr>
<td>$\eta$</td>
<td>12.4</td>
<td>12.4</td>
<td>12.4</td>
<td>12.4</td>
<td>12.4</td>
</tr>
<tr>
<td>GPP$_0^a$</td>
<td>255.0</td>
<td>255.0</td>
<td>255.0</td>
<td>255.0</td>
<td>255.0</td>
</tr>
<tr>
<td>$TdS^a$</td>
<td>68.2</td>
<td>85.2</td>
<td>102.2</td>
<td>119.2</td>
<td>136.2</td>
</tr>
<tr>
<td>Unsustainability ratio</td>
<td>6.3</td>
<td>7.9</td>
<td>9.5</td>
<td>11.1</td>
<td>12.7</td>
</tr>
<tr>
<td>$W_{crit}^a$</td>
<td>8.5</td>
<td>7.9</td>
<td>7.4</td>
<td>6.8</td>
<td>6.2</td>
</tr>
<tr>
<td>$\dot{Y}_{crit}^b$</td>
<td>5900</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalent erosion$^d$</td>
<td>22.7</td>
<td>28.4</td>
<td>34.1</td>
<td>39.7</td>
<td>45.4</td>
</tr>
</tbody>
</table>

$^a$GJ ha$^{-1}$ yr$^{-1}$

$^b$kg ha$^{-1}$ yr$^{-1}$

$^c$By mass, predominantly weeds, but also earth bacteria, viruses, fungi, worms, etc.

$^d$Based on Eq. (16).

The original chemical is ingested by a living organism (plant, fungus, insect, bacteria, or animal) and kills it or disrupts chemical signalling among species. Either way, the information contents of living organisms and their communications are destroyed and ecosystems are disrupted.

The chemical and its metabolic products can act at very low concentrations, essentially as a degrading catalyst of death:

Living organism $O_L +$ Field chemical $C \rightarrow$ Dead organism $O_D$

Dead organism $O_D \rightarrow$ Detritus $D + \epsilon_1 C + \epsilon_2 (1 - \epsilon_1) M$ [69]

or

$$O_L + C \rightarrow O_D$$
$$O_D \rightarrow D + \epsilon_1 C + \epsilon_2 (1 - \epsilon_1) M \rightarrow O_D$$
$$O_L + \epsilon_1 C + \epsilon_2 (1 - \epsilon_1) M \rightarrow O_D$$

where $\epsilon_1$ and $\epsilon_2$ are the fractions of the field chemical and its toxic metabolic products that persist after each round of ingestion. The reminders become nontoxic. This chain reaction catalyzed by $C$...

[70]

For example, a subset of organochlorine pesticides, agrochemicals, and environmental contaminants completely disrupts recruitment of rhizobia bacteria by leguminous plants, thus essentially stopping nitrogen sequestration by legumes (Fox et al., 2007).
TABLE 5
Results of calculation of entropy generation at the Lincoln, Nebraska, test site

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^a$</td>
<td>16.7</td>
</tr>
<tr>
<td>$Y^a$</td>
<td>241.3</td>
</tr>
<tr>
<td>$\dot{m}_{life}^{b,c}$</td>
<td>0.0</td>
</tr>
<tr>
<td>$D_{fc}^a$</td>
<td>0.0</td>
</tr>
<tr>
<td>$\eta$</td>
<td>14.4</td>
</tr>
<tr>
<td>$GPP_0^a$</td>
<td>255.0</td>
</tr>
<tr>
<td>$T_dS^a$</td>
<td>221.9</td>
</tr>
<tr>
<td>Unsustainability ratio</td>
<td>13.3</td>
</tr>
<tr>
<td>$W_{crit}^a$</td>
<td>8.9</td>
</tr>
<tr>
<td>$\dot{Y}_{crit}^b$</td>
<td>7200</td>
</tr>
<tr>
<td>Equivalent erosion$^d$</td>
<td>74.0</td>
</tr>
</tbody>
</table>

$^a$GJ ha$^{-1}$ yr$^{-1}$
$^b$kg ha$^{-1}$ yr$^{-1}$
$^c$By mass, predominantly weeds, but also earth bacteria, viruses, fungi, worms, etc.
$^d$Based on Eq. (16).

and $M$ stops after $n$ steps, when

$$C_{min} = \epsilon_1^2 C \log \left( \frac{C_{min}}{C} \right) = \frac{n}{\log \epsilon_1}$$

[71]

TABLE 6
Estimated average annual erosion rates of cultivated land USDA NRCS$^a$ in t ha$^{-1}$ yr$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas</td>
<td>34.3</td>
<td>31.4</td>
<td>26.9</td>
<td>26.9</td>
</tr>
<tr>
<td>Minnesota</td>
<td>19.1</td>
<td>20.9</td>
<td>19.5</td>
<td>17.7</td>
</tr>
<tr>
<td>Wyoming</td>
<td>17.7</td>
<td>21.1</td>
<td>20.2</td>
<td>16.4</td>
</tr>
<tr>
<td>Iowa</td>
<td>24.0</td>
<td>20.0</td>
<td>15.7</td>
<td>12.6</td>
</tr>
<tr>
<td>North Dakota</td>
<td>18.6</td>
<td>19.1</td>
<td>8.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Nebraska</td>
<td>14.4</td>
<td>13.2</td>
<td>11.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Michigan</td>
<td>11.2</td>
<td>11.7</td>
<td>11.0</td>
<td>9.9</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>11.0</td>
<td>9.6</td>
<td>9.0</td>
<td>8.8</td>
</tr>
<tr>
<td>National avg.$^b$</td>
<td>17.9</td>
<td>16.8</td>
<td>13.9</td>
<td>12.6</td>
</tr>
<tr>
<td>Mean$^c$</td>
<td>16.0</td>
<td>16.3</td>
<td>14.3</td>
<td>12.9</td>
</tr>
<tr>
<td>Std$^d$</td>
<td>7.2</td>
<td>9.1</td>
<td>8.3</td>
<td>7.8</td>
</tr>
<tr>
<td>Max erosion</td>
<td>36.6</td>
<td>55.4</td>
<td>43.8</td>
<td>47.1</td>
</tr>
<tr>
<td>Min erosion</td>
<td>4.7</td>
<td>4.5</td>
<td>4.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>

$^b$National average calculated by USDA.
$^c$The arithmetic mean calculated by USDA.
$^d$The standard deviation of state data.

FIG. 10. The histogram of estimated average annual water and wind erosion on cultivated land in the U.S., 1982–1997. All data are firmly lognormally distributed with the mean $\mu = 15$ and the standard deviation $\sigma = 8$ t ha$^{-1}$ yr$^{-1}$.

because the terms that involve $\epsilon_2$ decay much faster. Here $C_{min}$ is a threshold value of toxicity of $C$. If, for example, $C_{min}/C = 0.01$, and $\epsilon_1 = 0.5$, then $n \approx 7$. If $\epsilon_1 = 0.1$, $n \approx 2$. In the first case, our example field chemical recycles about 7 times, and its metabolic products 2–3 times, each time decaying in concentration, and eliminating unwanted life, as well as disrupting interspecies communications.

Neglecting the information content of the eliminated biomass, and if the field chemicals kill$^{21}$ $\dot{m}_{life} = 2500$ kg ha$^{-1}$ yr$^{-1}$ of mostly plants, the entropy generated by their decomposition will be $T_dS_{fc} = D_{fc} \approx 2.5 \times 17$ GJ ha$^{-1}$ yr$^{-1}$. In the calculations, we assume $\dot{m}_{life} = 0 \rightarrow 4000$ kg ha$^{-1}$ yr$^{-1}$. The mass of worms and their larvae which cause significant maize plant damage is minuscule, often less than 1 larva per plant.

G. CALCULATION RESULTS

The total entropy generated by an average U.S. maize field is listed in Table 4, for different mass of weeds and other life eliminated by field chemicals. This mass is varied between 0 and 4000 kg for a no-till field.

H. AVERAGE SOIL EROSION RATES IN THE USA

Estimated average annual sheet and rill erosion$^{22}$ plus wind erosion on nonfederal cultivated land, by state and year, are shown in Figure 9 and listed in Table 6. The 1982–1997 data set was revised by USDA in 2001. The histogram of all data is shown in Figure 10. From the data it follows that most erosion in the U.S. between 1982 and 1997 was $15 \pm 8$ t ha$^{-1}$ yr$^{-1}$. Since 1997,


$^{22}$Excluding gully erosion. Soils with unstable substrata, as loose sand and soft, decomposed rock, develop caving types of gulleys, which
FIG. 11. This dot density map shows areas where excessive erosion from wind and water occurred on cropland in 1997. Each darker (red) dot represents 5000 acres of highly erodible land eroding excessively (23 Mha). Each faint (yellow) dot represents 5000 acres of non-highly erodible land eroding excessively (20.4 Mha). Data are aggregated by 8-digit hydrologic units. Excessive erosion is defined as erosion greater than the tolerable rate. Highly Erodible Land is defined as land where the erodibility index is greater than or equal to 8. The Universal Soil Loss Equation is used to calculate water erosion. The Average Annual Wind Erosion Equation is used to calculate wind erosion. A total of 44 Mha eroded excessively in 1997, resulting in 1.3 billion tons of erosion. In instances where both sheet and rill and wind erosion were classified as excessive, area was counted only once to avoid double counting. Areas with 95% or more Federal area are shaded gray. Source: USDA-NRCS-RID, accessed Dec 27, 2007.

The estimated average erosion has been approximately $13 \pm 7 - 8 \text{ t ha}^{-1} \text{ yr}^{-1}$.

Figure 11 shows that excessive erosion has been widespread across the U.S. Corn Belt. The average national erosion rates reported by USDA for 2001 and 2003 were almost identical to that in 1997 (Anonymous, 2007), see Figure 9. One should note, however, that local erosion occurs mostly during extreme rain and wind events, and actual erosion rates are perhaps 10 - 100 times higher than the spatially and temporally averaged predictions in Figure 9 and Table 6. For example, direct measurements of sediment loads in the upper Mississippi River and the Illinois River by Gaugush (1999) showed that intensive maize agriculture increases erosion rate by a factor of 20. Kirchner et al. (2001), in turn, have shown that the long-term sediment yields from mountain slopes are, on average, 17 times higher than stream sediment fluxes measured over 10 to 84 years. Their results imply that conventional sediment-yield measurements—even those made over decades—can greatly underestimate long-term average rates of sediment delivery from uplands.

are always exceedingly difficult to control. Soils with impervious clay subsoils, on the other hand, develop V-shaped gulleys, which are much easier to control, as a rule. Those soils having substrata of exceptionally high silt content yield readily to the formation of deep gulleys with vertical walls. This is notably true of the Memphis silt loam and similar types of the loessial country skirting the Mississippi and Missouri Rivers in parts of the Corn Belt (Bennett, 1931).