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# Assessing Environmental Sustainability Using Ecological Limits Expressed as Mass Flowrates with the Inclusion of a Sustainable Time Perspective

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**Abstract:** This study explores the concept of ecological limits (*EL*s) for determining the sustainable extraction of natural resources and sustainable discharge of emissions. *EL*s are expressed as limiting mass flowrates and equations are developed and presented for their quantitative estimation. These include a sustainable time perspective term. This is a time duration that provides sufficient time for humans to adapt to the depletion of a resource stock or emission budget, e.g., the time for a number of human generations. Thus, even if a resource is utilised at a greater rate than its regeneration rate, it could be considered sustainable if the resource extraction rate is adjusted so that the stock continuously lasts for more than the sustainable timeframe. The application of this ecological limits concept is illustrated by applying it to assessing the environmental sustainability of global fossil fuel energy, specific water resources, and global fertilisers. Exceeding *EL*s can act as a warning signal and highlight those resources and emissions where actions need to be taken to bring their extraction and discharge rates to within the *EL*s.

**Keywords:** ecological limits; environmental sustainability; natural resource extraction; emissions discharge

## 1. Introduction

Sustainability can be described as people (globally) being able to "flourish" [1] over a "prolonged period" of time. "Flourish" could be described as providing at least basic needs, including food, water, sanitation, shelter, healthcare, and education. "Prolonged period" of time could be described as, in human terms, as being many generations, for example thousands of years. The sustainability of human flourishing is often described in terms of incorporating the inter-relationship between the three domains of environmental, economic and social [2]. It could be argued that environmental sustainability is the foundation to sustainability in the sense that humanity needs the natural environment if it is to flourish. Humanity is on an unsustainable path from an environmental perspective [3–5] because there are ecological limits that have been surpassed or are on the way to being surpassed, as humanity extracts a vast amount of natural resources and discharges a vast amount of wastes [6,7].

Engineering and technology have much to offer in moving humanity back towards a sustainable paradigm. Developing greener technologies and greatly improving natural resource utilization efficiencies are very important in the move towards a sustainable paradigm. However, application of engineering and technology in the current dominant socio-economic paradigm may only be producing benefits to humanity in the short-term. It could be argued that engineering and technology are only accelerating humanity faster along an unsustainable path [8]. This is unsustainable and may be detrimental to humanity in the longer-term. Within this paradigm of the relentless desire for economic growth and consumption, engineering and technology are accelerating unsustainable extraction of materials and discharge of wastes and emissions to beyond ecological limits [4].

Jackson [9] presents a concise history of ecological limits as having three distinct phases. The first being in the late 18th century with the assertion by Thomas Malthus that growth in human population would be limited by the pace of growth in the resources available to feed and shelter people. The second phase was the "Limits to Growth" study [4] in the early 1970s where systems dynamic modelling showed that increasing scarcity of natural resources and/or increasing pollution could impact on the global economy, causing economic collapse and reduction in human population and welfare. This study highlighted that there are limits to the extraction of natural resources and discharge of emissions if a sustainable economy, human population, and welfare are to be achieved. The third phase focused on the emissions of greenhouse gases (GHGs) and climate change, and the need to limit these emissions so as to prevent their atmospheric concentrations increasing to levels that could cause dangerous climate change.

For a sustainable economy and the sustainability of human flourishing, it is first important to recognise that the economy must exist within ecological limits. It is then necessary to clearly identify and quantify these limits so that action plans can be devised to keep an economy within these limits. This is a key concept to achieving and maintaining a sustainable economy [10,11]. Furthermore, a sustainable economy (an economy that functions within ecological limits) is required to provide the necessary context within which engineers and scientists can deliver technological improvements to people's well-being that are sustainable and beneficial to humanity in the long-term. There are a number of approaches reported that endeavor to define and quantify limits that can be referred to as ecological limits, in particular, the ecological footprint and planetary boundaries approaches.

Ecological footprint analysis [12,13] quantifies the productive surface area required that a given population requires to produce the natural resources it consumes (including food and fiber products, and space for urban infrastructure) and to absorb its carbon emissions. This surface area is expressed using six categories: cropland, grazing land, fishing grounds, built-up land, forest area, and land required to absorb carbon emissions. This can be done for an individual and the population in a city, country and on planet earth. The biocapacity of a specific area—such as a region, or country, or planet earth—is the productive surface area that is contained within this region. For the human population on planet earth, comparing its ecological footprint with the biocapacity of the planet is a simple and useful index for assessing the environmentally sustainability of the population. The biocapacity of the planet can be considered as an ecological limit and to be environmentally sustainable, the ecological footprint should be less than the biocapacity. In 2017, it was 1.6 times the biocapacity and is thus very unsustainable from an environmental perspective using this index. Fujii et al. [14] highlight that this is an easily understandable indicator, but its scope is somewhat limited as some important aspects cannot be converted into a land area, such as depletion of mineral resources. Furthermore, Fiala [15] highlights other important limitations of ecological footprinting to assessing environmental sustainability, such as, it does not address the issue of land degradation or the impact of technological progress on the land area requirements for crop production.

The planetary boundaries concept was introduced by a group of scientists led by Johan Rockström, which consisted of nine planetary boundaries, including climate change, ocean acidification, and biogeochemical flows [16–18]. These boundaries can be described as being human determined control variables, such as global atmospheric carbon dioxide concentration, that are set at a 'safe' distance from a dangerous value that could cause major environmental change, such as dangerous global warming. These planetary boundaries can be considered as ecological limits.

As mentioned above, humanity needs the natural environment if it is to flourish. A major aspect of this is that it needs the natural environment to continuously provide natural resources and to deal with its wastes continuously over time for humanity to sustain itself and prosper. Consequently, major aspects of environmental sustainability are (Figure 1):

- Sustainable natural resource extraction.
- Sustainable discharge of wastes/emissions into the natural environment.

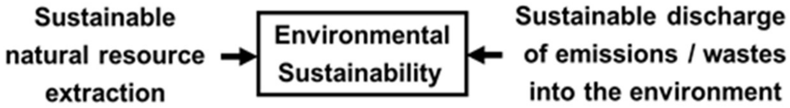

**Figure 1.** Key aspects of environmental sustainability.

There are ecological limits, as mentioned earlier, and thus there are limits to the extraction of natural resources and discharge of wastes/emissions if humanity is to continue to flourish over a prolonged period of time. In this work, these ecological limits are expressed as limiting mass flowrates, which is somewhat similar to the limiting rates proposed by Daly [19]. Daly suggests that harvest rates of renewable resources should equal their regeneration rates; waste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted; and the rate of depletion of non-renewables should be limited to the rate of creation of renewable substitutes. It could be argued that these limits are potentially too strict and larger values could be applied while still remaining sustainable. A key concept presented here, and applied to the evaluation of ecological limits, is the inclusion of a sustainable time perspective. For a natural resource, this represents a timeframe or time duration, e.g., a number of human generations, such that the extraction rate should not deplete the resource 'stock' in less than this time. Likewise, for an emission, the discharge rate should not deplete the emission 'budget' in less than this time. To be environmentally sustainable at any point in time, the depletion time must be greater than the sustainable timeframe.

The objectives of the paper are to more clearly explore the ecological limits concepts by defining ecological limits as limiting mass flowrates and expressing them quantitatively in a clear equation format, and to include the sustainable time perspective highlighted above. The equations are then applied to aspects of the food-energy-water nexus as a means to illustrating the application of the ecological limits concepts presented in the paper.

## 2. Ecological Limits and the Inclusion of a Sustainable Time Perspective

In this paper, ecological limits ($ELs$) are expressed as mass flowrates. They are upper limits on sustainable rate of natural resource extraction and discharge of emissions. Some $ELs$ may be considered global, such as greenhouse gas emissions, while others are local, such as water extracted from a local aquifer.

### *2.1. Ecological Limits of Renewable and Non-Renewable Resources*

The ecological limit of a natural resource ($EL_{NR}$) could be described as being equal to the rate of regeneration of the resource, as given in Equations (1) and (2). Regeneration can be both natural, e.g., renewable resources, and human, e.g., recycling. In this scenario, the stock of the resource is not depleted if the extraction rate is less than or equal to the regeneration rate.

$$EL_{NR} = RR \tag{1}$$

$$RR = RR_N + RR_H \tag{2}$$

where:

$RR$: Total regeneration rate of the natural resource
$RR_N$: Natural regeneration rate
$RR_H$: Human regeneration rate

It could be argued that this is an unrealistic ecological limit (*EL*), e.g., for non-renewables, or too strict a definition of an *EL* and that the *EL* could be larger. For example, if the resource stock is very large relative to the extraction rate, then some stock depletion could be allowed and the *EL* could be larger. Sustainability of resource extraction is the ability to sustain the extraction of a resource over time, ideally infinite time, but the earth is inherently environmentally unsustainable, as it will eventually stop supporting life at some stage in the future. Consequently, there is a time perspective to this analysis and this needs to be considered. The sustainable timeframe could be chosen as to provide enough time for humans to adapt to the resource being depleted, e.g., the time for a number of human generations, such as 200 years. Thus, even if the resource is utilised at a greater rate than its regeneration, it could be considered sustainable at a given point in time if the stock lasts for more than the sustainable timeframe at that extraction rate. From this analysis, the present *EL* for a resource ($EL_{NR}$) is given in Equation (3)

$$EL_{NR} = \frac{Stock}{t_S} + RR \tag{3}$$

where:

*Stock*: Mass of the resource present in nature that has potential for being extracted at some time in the future.

$t_S$: The sustainable timeframe for humans to adapt to the resource being depleted (This may vary between resources depending on their perceived criticality and substitutability).

This may lead to the stock decreasing over time, and thus may lead to the $EL_{NR}$ also decreasing over time. The idea of a decreasing resource stock (or emission budget) may appear unreasonable, however this is explored further in Section 2.6.

### 2.2. Ecological Limits of Waste/Emission Discharges into the Natural Environment

Firstly, from an environmental sustainability perspective, the emission of materials into nature that are likely to harm the environment or harm humanity should only be considered. It could be argued that discharging some materials into a landfill may not be causing any harm from an emissions perspective. For example, it could be argued that dumping iron or aluminium in a landfill is not harming humanity or the environment; it is essentially moving material from hole to another.

Considering the above, a similar analysis to that in Section 2.1, is applied to discharge of wastes/emissions to the natural environment that have the potential to harm nature and humanity. The ecological limit of such a waste/emission to nature ($EL_{WE}$) could be described as being equal to the rate of assimilation of the emission, as given in Equations (4) and (5). Assimilation can be both by nature (e.g., $CO_2$ assimilation by plants, algae and the oceans) and by humanity (e.g., carbon capture, storage and utilisation). In this scenario, the 'concentration' of the emitted component does not increase in nature such that it can cause harm.

$$EL_{WE} = AR \tag{4}$$

$$AR = AR_N + AR_H \tag{5}$$

where:

*AR*: Overall total assimilation rate of the emission/waste
$AR_N$: Natural assimilation rate
$AR_H$: Human assimilation rate

Like natural resource extraction, it could be argued that this is an unrealistic *EL* or too strict a definition of an *EL* and that the *EL* could be larger. For example, if the emission rate is causing an increase in the 'concentration' of the component in nature but that it would take a long time for the 'concentration' of the material to cause harm, then the *EL* could be larger. This leads to the concept of a 'budget'. This is the mass of component that can be absorbed into the environment (or compartment within it, such as atmosphere or ocean) that would increase the concentration from the current level to a critical level that is likely to cause the onset of significant harm. For example, the European Environmental Agency [20] believe that the global $CO_{2\,eq}$ concentration in the atmosphere should be limited to 530 ppm, in order to inhibit the occurrence of dangerous climate change. In 2014, the global concentration was less than this at 441 ppm, consequently, there is a mass of emissions or budget that can be absorbed by the atmosphere before 530 ppm is attained. Similar to the natural resource extraction, a sustainable timeframe could be chosen as to provide enough time for humans to adapt to the budget being depleted, e.g., 200 years, thus even if the emission rate is greater than the assimilation rate (and the budget is being reduced), it could be considered sustainable if the budget lasts for more than the sustainable timeframe. From this analysis, the present $EL$ for a waste/emission ($EL_{WE}$) is given in Equation (6).

$$EL_{WE} = \frac{Budget}{t_S} + AR_N + AR_H \tag{6}$$

where:

*Budget*: This is the mass of component that can be absorbed into the environmental (or compartment within it) which increases the current concentration of the emission in the environment up to an agreed 'onset of harm' concentration.

$t_S$: The sustainable timeframe for humans to adapt to the budget being depleted. This may vary between wastes/emissions depending on their perceived harmfulness and importance of benefits that give rise to the waste/emission.

### 2.3. Application of Ecological Limits to Assessing Environmental Sustainability

The ecological limits outlined above could be applied to assess both the environmental sustainability of natural resource extraction and waste/emission discharges into nature. For the natural resource to be environmental sustainability, then the rate of extraction of the natural resource ($RU_{NR}$) must be less than or equal to its ecological limit, as in Equation (7).

$$RU_{NR} \leq EL_{NR} \tag{7}$$

Otherwise, it is environmentally unsustainable.

Likewise, for a waste/emission to be environmentally sustainable, the rate of discharge of the waste/emission into the environment ($RD_{WE}$) must be less than or equal to its ecological limit, as in Equation (8).

$$RD_{WE} \leq EL_{WE} \tag{8}$$

Otherwise, it is environmentally unsustainable.

Alternatively, it may be more informative to normalise both Equations (7) and (8), as expressed in Equations (9) and (10). This can provide a better indication of environmental sustainability or unsustainability. For example, if the ratio is a lot greater than 1, then this provides a measure of how severe the environmental unsustainability is. Once a ratio exceeds one, this acts as a warning signal indicating environmentally unsustainable resource extraction or emissions discharge rates, and that future actions need to be taken so as to reduce the ratio to less than one.

$$\frac{RU_{NR}}{EL_{NR}} \leq 1 \tag{9}$$

$$\frac{RD_{WE}}{EL_{WE}} \leq 1 \tag{10}$$

The use of the equations above rely on being able to estimate values for stocks, budgets, regeneration and assimilation rates. All of this may prove difficult and will usually involve much work to estimate these data. This is the job of a whole variety of professionals with expertise and capability to obtain the relevant data, although much data is available in the literature. Goodland [21] highlights that there can be much uncertainty in the application of environmental sustainability concepts, however indicators providing rough estimates are of value so that progress can be made.

### 2.4. Complementary Approach Using Depletion Times of Stocks and Budgets

The depletion times of resource stocks and emission budgets can be used as an alternative to the equations presented in Sections 2.1–2.3 for assessing the environmental sustainability of natural resource extraction or emission discharge. The time required to deplete the stock of a natural resource ($t_{dS}$) is given in Equation (11).

$$t_{dS} = \frac{Stock}{(RU_{NR} - RR)} \tag{11}$$

The resource extraction is considered environmentally sustainable if the stock depletion time is greater than the sustainable timeframe as presented in Equation (12)

$$t_{dS} \geq t_S \tag{12}$$

Likewise, the time required to deplete the budget ($t_{dB}$) of an emission is given in Equation (13).

$$t_{dB} = \frac{Budget}{(RD_{WE} - AR)} \tag{13}$$

The emission discharge is considered environmentally sustainable if the budget depletion time is greater than the sustainable timeframe as presented in Equation (14)

$$t_{dB} \geq t_S \tag{14}$$

The use of time indicators, such as comparing the depletion times to a sustainable timeframe, may act as a more intuitive and effective means of communicating to people [22] whether or not natural resource extraction or emission discharge is environmentally sustainable.

### 2.5. Ecological Limits and Depletion Times as Warning Signals for Action

Resource extraction or emission discharges being greater than ecological limits, and depletion times that are lower than the sustainable timeframe, can act as warning signals indicating environmentally unsustainable resource extraction or emissions discharge, and that future actions need to be taken to restore environmental sustainability. For natural resources, the stock depletion time ($t_{dS}$) needs to be increased such that $t_{dS} \geq t_S$. Equation (11) highlights this can be achieved by reducing resource extraction and/or increasing regeneration rate. This may be achieved over time by implementing measures, such as using socio-economic approaches to reduce demand, finding substitutions, and improving the ability to increase recycling. For restoring the environmental sustainability of emissions/wastes, the budget depletion time ($t_{dB}$) needs to be increased such that $t_{dB} \geq t_S$. Equation (13) highlights this can be achieved by reducing emission's discharge and/or increasing assimilation rate. This may be achieved over time by implementing measures, such as using socio-economic approaches to reduce discharges (e.g., carbon taxation on carbon emissions), and improving the ability to increase assimilation (e.g., by carbon capture, and storage and utilisation of carbon emissions).

### 2.6. Sustainable Time Perspective, Reduction of Stocks and Budgets, and Varying Regeneration and Assimilation Rates

The inclusion of a sustainable time perspective ($t_S$ in Equations (3) and (6)) may result in the reduction of stocks and budgets over time. This may appear unsustainable, however, the overarching idea to the sustainable time perspective is that there is at least $t_S$ (e.g., 200 years) for humanity to adjust before a resource or budget is depleted, and that this should represent sufficient time for humanity and future generations to adjust. At each future time, resource extraction or emissions discharge would be considered environmentally sustainable if the depletion times in Equations (12) and (14) are greater than the sustainable time frame ($t_S$) at a particular future time.

There is an issue with this approach in relation to the resource regeneration rate (RR) and emission assimilation rate (AR). For natural resources, the stock depletion time in Equation (11) assumes that the regeneration rate (RR) does not change over the course of time. In reality, it most likely will change. In some cases, such as a fish stock, RR will be related to the size of the stock and will decrease as the stock decreases, thus reducing the stock depletion time from that calculated in Equation (11). On the other hand, technology could help increase RR over time, for example by increasing recycling, and this could increase the stock depletion time. Considering the potential for future variations in RR, the environmental sustainability indicators of a resource extraction (Equations (7) and (12)) represent approximate indicators based on values for stock and RR with reference to a particular year, in the knowledge that future values of RR could decrease or increase over time. Likewise, for an emission, AR could vary over time and thus the environmental sustainability indicators of an emission discharge (Equations (8) and (14)) represent approximate indicators based on values for budget and AR with reference to a particular year.

### *2.7. Ecological Limits: Local and Global*

The EL concept can be applied both at local and global level. For example, it can be applied to assessing the environmental sustainability of the extraction of groundwater from a specific aquifer and it can be applied to global aggregate groundwater extraction. Likewise, for wastes and emissions, it can be applied to a specific emission being emitted locally and its impact on the local area and to global impact of emissions like greenhouse gases.

### *2.8. Interaction Among Ecological Limits and Dependence on Multiple Ecological Limits*

The work on planetary boundaries highlighted that the interaction among planetary boundaries may shift the safe level (or limit) of one or several boundaries [16]. For example, operating at near to the freshwater extraction limit may cause increases in species extinction rate that exceed the biodiversity limit, thus the freshwater extraction limit may need to be reduced to prevent the biodiversity limit being exceeded.

Likewise, with ecological limits, the rate of a specific resource extraction or discharge of a specific emission may influence the ecological limits of other resources and emissions. For example, increasing the emissions of greenhouse gases into the atmosphere can alter climate which can affect rainfall patterns which can influence the regeneration rate of a water resource and thus influence its ecological limit. Reducing the stock of forest in the Amazon can influence rainfall patterns that can also influence the *EL*s of water resources. It can also influence carbon assimilation rate which will influence the EL of carbon emissions to atmosphere.

The environmental sustainability of a natural resource, such as a forest or fishery, depends on the sustainability of the natural resources/services that sustain it [21]. Consequently, the ecological limit of many natural resources, such as sustainable production of food and fibre, inherently depends on many other ecological limits, such as the ecological limits associated with energy requirement, fertiliser components and water. This is explored further in Section 3.

### *2.9. Ecological Limits and Depletion Times Are Dynamic*

Ecological limits and depletion times are typically not fixed values; they can vary with time. There are a number of reasons for this. *EL*s and depletion times will inherently vary due to their definition in the equations above. If stocks and budgets are being depleted from year to year, then this will result in a reduction in *EL*s and depletion times from year to year. If RR and AR vary, then *EL*s and depletion times will also vary, as highlighted in Section 2.6. Furthermore, natural fluctuations in nature will cause variations, such as variations in rainfall which influence the regeneration rate in water systems. There may also be interactions with other resources and emissions which may influence the *EL* of a specific resource or emission, as highlighted in Section 2.7.

## 3. Ecological Limits and the Food–Energy–Water (FEW) Nexus

Major environmental sustainability issues world-wide are associated with supply of food, energy and water to people and the wastes/emissions associated with them [23–25]. This is oftentimes referred to as the food–energy–water (FEW) nexus. This section applies the concepts of ecological limits outlined in Section 2 to the FEW nexus. This is done in a very approximate manner, using relevant data sourced from the literature, simply to illustrate the application of the ecological limits concepts as presented in this paper.

### 3.1. Energy

The environmental sustainability of energy can be assessed both in terms of the sustainability of the natural resource extraction and the sustainability of emissions to the environment. At a global scale, the dominant natural resources used to supply energy are fossil fuels. Data for proven fossil fuel reserves and annual extraction rates (as of 2014) were obtained from British Petroleum [26] and these data are provided in Table 1, along with the ecological limits and depletion time calculations. These data show that the extraction of fossil fuels are environmentally unsustainable from a 200 year sustainability time perspective.

**Table 1.** Environmental sustainability assessment of global fossil fuel resources [$t_S$ = 200 years] (units: *stock*–giga tonnes oil equivalent (GTOE); *RR*, $EL_{NR}$, $RU_{NR}$–GTOE year$^{-1}$).

| Resource | *Stock* [1] | *RR* | $EL_{NR}$ | $RU_{NR}$ [1] | $\frac{RU_{NR}}{EL_{NR}}$ | $t_{dS}$ (Years) |
|---|---|---|---|---|---|---|
| **Fossil Fuels—Global** | | | | | | |
| Total | 840 | 0 | 4.20 | 11.2 | 2.67 | 75 |
| Oil | 240 | 0 | 1.20 | 4.2 | 3.50 | 57 |
| Natural gas | 169 | 0 | 0.85 | 3.1 | 3.67 | 55 |

[1] Reference: [26]; *Stock* is proven reserves that have a reasonable certainty of being recovered in the future from known reservoirs under existing economic and operating conditions.

There are a number of emissions of concern from the burning of fossil fuels for energy, but the most pressing ones are GHG emissions, in particular $CO_2$, and their impact on climate change. Energy production and use (including fuels used by vehicles) represent the largest source of GHG emissions globally with about 71% of the total in 2010 [27]. Looking at the sustainability of GHG emissions, the GHG budget depends on what is a 'safe' limit for average global GHG concentration in the atmosphere to provide a reasonable likelihood of averting dangerous climate change. Staying within 1.5 °C or 2 °C in global mean temperature is often quoted as what is required to avert dangerous climate change. The European Environmental Agency [20] suggests that the concentration of GHGs and other forcing agents (including aerosols) should be kept below 430 ppm or 530 ppm of $CO_{2\,eq}$ to have a 50% probability of staying below a 1.5 °C or 2 °C, respectively, increase in global mean temperature from pre-industrial times. They report that the $CO_{2\,eq}$ concentration was 441 ppm in 2014, thus the budget has already been used up in the context of a 1.5 °C rise. In the context of a 2 °C rise, a budget of 691 Gt $CO_{2\,eq}$ was calculated based on a 89 ppm increase in atmospheric $CO_{2\,eq}$ concentration (from 441 to 530 ppm). This was estimated by multiplying 89 ppm by a factor of 2.12 to estimate the increase in the mass of carbon in the atmosphere [28,29] and then multiplying this by 3.664 to calculate the corresponding $CO_{2\,eq}$. Le Quéré et al. [28] present a global natural assimilation rate of $CO_2$ of around 18 Gt year$^{-1}$. The Intergovernmental Panel on Climate Change [30] present that global GHG emissions were discharged at a rate of around 50 Gt year$^{-1}$. These data were applied in Table 2 to estimate the ecological limit of GHG emissions and the $CO_{2\,eq}$ budget depletion time.

It shows that the discharge of GHG emissions is very environmentally unsustainable with a budget depletion time of only 22 years, with reference to the year 2014.

**Table 2.** Environmental sustainability assessment of global greenhouse gas (GHG) emissions [$t_S$ = 200 years] (units: *Budget*–giga tonnes (Gt) of $CO_{2\ eq}$; $EL_{WE}$, $RD_{WE}$–Gt of $CO_{2\ eq}$ year$^{-1}$).

| Emission | *Budget* [1] | $AR_N$ [1] | $EL_{WE}$ | $RD_{WE}$ [2] | $\frac{RD_{WE}}{EL_{WE}}$ | $t_{dB}$ (Years) |
|---|---|---|---|---|---|---|
| GHG—global | 691 | 18 | 21 | 50 | 2.3 | 22 |

[1] Reference: [28]; [2] reference: [30].

### 3.2. Water

The ecological limits analysis was applied to examples of both groundwater and surface water. The high plains or Ogallala aquifer in the USA is a very large aquifer that supplies groundwater to important agricultural regions in the American mid-west. Data was sourced from the US Geological Survey [31,32] to assess the environmental sustainability of water extraction using the ecological limits approach and this is presented in Table 3. The data presented for stock, $RD_{WE}$ and $RR$ are average estimates. McGuire [31] reports that the water in storage or stock is about 2.9 billion acre-ft (~3500 Gt). Assuming that 25% is not useable, then the stock is around 2600 Gt. The depletion time in Table 3 is greater than 200 years thus water extraction is environmentally sustainability from a 200-year sustainability time perspective. However, there are a number of issues with these results. The aquifer covers a large area and there are large variations in the data depending on the specific region. For example, many regions in Texas [33] have depletion times that could be less than 50 years. Thus, extraction of water in these regions is environmentally unsustainable and action needs to be taken to try and address this. Improvements in water extraction efficiency can reduce $RU_{NR}$ but in many regions like in Texas, the aquifer recharge rate is essentially zero as rainfall is counteracted by water loss in particular due to evapotranspiration. Thus, these regions will become totally depleted of useful water and this is a huge problem to address. On the other hand, other parts of the aquifer, particularly in Nebraska, could have much longer depletion times than the value given in Table 3. McGuire [31] has even reported that water levels in some wells in Nebraska actually increased during 2007 to 2009.

**Table 3.** Environmental sustainability assessment of freshwater resources [$t_S$ = 200 years] (units: *stock*–Gt; $RR$, $EL_{NR}$, $RU_{NR}$–Gt year$^{-1}$).

| Resource | *Stock* | $RR$ | $EL_{NR}$ | $RU_{NR}$ | $\frac{RU_{NR}}{EL_{NR}}$ | $t_{dS}$ (Years) |
|---|---|---|---|---|---|---|
| **Ground water** | | | | | | |
| Ogallala aquifer | 2600 [1] | - | 13 | 10.2 [2] | 0.78 | 255 |
| **Surface water** | | | | | | |
| Colorado river | 74 | 20.2 [3] | 20.6 | 18.9 [3] | 0.92 | −57 |

[1] Reference: [31]; [2] reference: [32]; [3] reference: [34].

The Colorado river is the major supplier of water to the south western United States. The 100-year (up to 2011) average natural flow of the Colorado is about 16.4 million acre-ft year$^{-1}$ (~20.2 Gt year$^{-1}$) and the 10 years average (up to 2011) water resource extraction rate is about 15.4 million acre-ft (~18.9 Gt year$^{-1}$) [34]. Rivers are like continuous water flow systems where water originates from the atmosphere and rains onto the river basin, moving into the river and flowing back to the sea. The stock for the river is dynamic; it is basically the mass of water in the river basin at any one time. For the Colorado river, the average is about 60 million acre-ft (74 Gt) which is nearly 4 years of the natural yearly flow [34]. The system is environmentally sustainable as presented in Table 3, with an extraction to ecological limit ratio less than 1. The depletion time is negative, but this occurs mathematically in Equation (11) when the resource extraction rate is less than the resource recharge rate and is thus inherently sustainable. However, the ratio is near to one, indicating that there is little further capacity to satisfy increased future demand.

### *3.3. Food and Agriculture*

Modern agricultural production currently produces a huge amount of food. It produces very high yields per hectare with typically very good quality produce. There are many natural systems that influence modern agriculture and some of the key ones include:

- Energy for mechanisation
- Water for irrigation
- Production of fertilisers (in particular, nitrogen-, phosphorus-, and potassium-based)
- Production of pesticides & herbicides
- Soil quality and degradation

The environmental sustainability of these systems influence the environmental sustainability of food production by modern agriculture. In this section, the concepts of ecological limits developed in this paper are applied to some of these, as part of assessing the environmental sustainability of modern agriculture. As mentioned earlier, this is done in a very approximate manner with the aim of illustrating the application of the ecological limits concepts to a complex system depending on multiple ecological limits.

#### 3.3.1. Energy

Modern agriculture is highly dependent on mechanisation. This depends on energy which mainly comes from fossil fuels. Consequently, the environmental sustainability of energy in modern agriculture depends on the sustainability of fossil fuels, which is shown in Section 3.1 to be environmentally unsustainable from both a fossil fuel resource perspective and from the perspective of GHG emissions and climate change. This is a particular cause of concern for modern agriculture globally.

#### 3.3.2. Water

In some regions of the world, there is plenty of rainfall and little need for irrigation while in others there is a requirement to source water for irrigation. Water may be sourced from an aquifer or surface water. Ecological limits analysis presented in this work can be applied to assessing the environmental sustainability of water extraction in a particular region by applying the concepts to a particular aquifer or surface water source, as highlighted in Section 3.2. Once again, there can be interactions with other ecological limits, for example limits on GHG emissions can influence climate change which can influence precipitation patterns which in turn can influence the limits associated with water sources.

#### 3.3.3. Fertilisers

The main fertilisers used in modern agriculture are nitrogen, phosphorus, potassium, and sulphur. Sulphur is one of the more common constituents of the Earth’s crust and consequently should not be a limiting fertiliser for agriculture. Phosphorus and potassium fertilisers are obtained from mining rock phosphate and potash, respectively. Fixen and Johnston [35] provide approximate estimates of global reserves, reserve base and mine production rates and these are presented in Table 4. Reserves represent that part of the reserve base that can be economically exploited while the reserve base also includes resource that is currently uneconomic to exploit. Considering the data in Table 4 the reserves data suggest that phosphate is unsustainable and should be of concern. From a reserve base perspective both phosphate and potash have depletion times of 280 and 500 years, respectively, which means that they are environmentally sustainable from a resource extraction perspective. However, both are non-renewable resources and thus will become unsustainable at some point in the future. Nitrogen fertilisers are manufactured from ammonia, which in-turn is mainly manufactured from natural gas or fossil methane [35]. It can be seen in Table 1 that the resource depletion time of natural gas is about 55 years, which is well below the 200 years sustainability time perspective, thus it is environmentally unsustainable and a cause for concern.

**Table 4.** Environmental sustainability assessment of phosphate and potash resources [$t_S$ = 200 years] (units: *stock*–million tonnes; *RR*, $EL_{NR}$, $RU_{NR}$–million tonnes year$^{-1}$).

| Resource | *Stock* [1] | *RR* [1] | $EL_{NR}$ | $RU_{NR}$ [1] | $\frac{RU_{NR}}{EL_{NR}}$ | $t_{dS}$ (Years) |
|---|---|---|---|---|---|---|
| **Fertilisers global** | | | | | | |
| Phosphate | | | | | | |
| Reserves | 15,000 | 0 | 75 | 167 | 2.23 | 90 |
| Reserve base | 47,000 | 0 | 235 | 167 | 0.71 | 280 |
| Potash | | | | | | |
| Reserves | 8300 | 0 | 41.5 | 36 | 0.87 | 230 |
| Reserve base | 18,000 | 0 | 90 | 36 | 0.4 | 500 |

[1] Reference: [35].

The above analysis has focussed on assessing environmental sustainability from a natural resource perspective however it should also be analysed from an emissions perspective. Steffen et al. [18] states that human activities globally fix nitrogen (N) at about 150 Mt N year$^{-1}$ into reactive N. Roughly 80% of this is fixed to reactive N in the form of ammonia and via the cultivation of leguminous crops [16,17]. Much of this reactive N eventually ends up in the environment. They also state that the discharge limit should be about 62 Mt N year$^{-1}$. As the discharge mass flowrate is well above the ecological limit, this exceeds the planetary boundary and is environmentally unsustainable from Equations (4) and (8). Steffen et al. [18] also provide approximate data for global phosphorus (P) discharge of 22 Mt P year$^{-1}$ from freshwater systems into the environment which is double their planetary boundary of 11 Mt P year$^{-1}$ and also environmentally unsustainable from Equations (4) and (8).

### 3.3.4. Soil Quality and Degradation

Martenson [36] highlights the quest to grow more food, more cheaply, on the same amount of land, year after year, has resulted in strip-mining the soil of its essential nutrients and qualities and converting it into lifeless dirt. Consequently, the issue of soil quality and degradation and its impact on the environmental sustainability of modern agriculture is of concern. However, the ecological limits approach presented in this paper may not be a suitable approach for assessing soil quality and its environmental sustainability. Thus, this highlights the point that other approaches may be more suitable for assessing the environmental sustainability of some aspects of complex systems like soil quality in modern agriculture.

## 4. Conclusions

Environmental sustainability is crucial to the sustainability of human flourishing and the functioning of a sustainable economy, which provides the context in which engineers and scientists can apply their knowledge and skills for the long-term benefit of humanity. Environmental sustainability may be viewed in terms of sustainable extraction of natural resources and sustainable discharge of emissions into nature. This study explored the concept of ecological limits as being limiting mass flowrates to the sustainable extraction of natural resources and sustainable discharge of emissions and are presented in a clear quantitative equation format.

The *EL* of a natural resource could be described as being equal to the rate of natural and human regeneration of the resource. This could be considered to be unrealistic for non-renewable resources and too strict a definition if the resource stock is very large relative to the extraction rate, consequently some stock depletion could be allowed and the *EL* could be larger. Sustainability of resource extraction is the ability to sustain the extraction of a resource over time, ideally infinite time but the earth is inherently environmentally unsustainable, as it will eventually stop supporting life at some stage in the future. Consequently, there is a time perspective to this analysis and this needs to be considered. The sustainable timeframe could be chosen as to provide enough time for humans to adapt to the resource depletion, e.g., the time for a number of human generations, thus even if the resource is utilised at a greater rate than its regeneration, it could be considered sustainable if the stock lasts for more than the sustainable timeframe. A key point to appreciate is that this condition must be maintained continuously over time. This may necessitate a consequential reduction in extraction rate of a particular resource over time, which will require human progress to implement measures that can facilitate this, such as increases in recycling ability and reducing demand. A similar conceptual analysis was applied to the limiting mass flowrates associated with the discharge of wastes/emissions into the natural environment.

The equations used for evaluating the ecological limits are also applied in developing equations for estimating depletion times of resource stocks and emission budgets. This is applied as a complementary approach to using the equations for assessing the environmental sustainability of resource extraction and emission discharge. Comparison of depletion times with the sustainable timeframe is potentially a more intuitive and effective means of communicating the environmental sustainability of natural resource extraction and emission discharge.

The usefulness of *ELs* as limiting mass flowrates is that they can identify natural resources that are being extracted unsustainably and emissions that are being discharged unsustainably into nature. This can act as a warning signal and highlight those resources and emissions where actions need to be taken to bring their extraction and discharge rates to within the *ELs*. This is a key aspect in trying to achieve and maintain a sustainable economy.

The future direction of this work is in the application of the equations for assessing the environmental sustainability of critical natural resources and emissions, including those associated with the food–energy–water nexus in various regions of the globe. Key to this endeavor is the sourcing of good quality data to insert into the equations. The approach described in this paper cannot assess all aspects of environmental sustainability, consequently it is important to identify aspects where it is not appropriate and the approaches that are appropriate, so as to facilitate the application of a variety of complementary approaches for assessing environmental sustainability.

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