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An Analysis of the Potential for the Formation of 'Nodes of Persisting Complexity'

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Abstract: Human civilisation has undergone a continuous trajectory of rising sociopolitical complexity since its inception; a trend which has undergone a dramatic recent acceleration. This phenomenon has resulted in increasingly severe perturbation of the Earth System, manifesting recently as global-scale effects such as climate change. These effects create an increased risk of a global 'de-complexification' (collapse) event in which complexity could undergo widespread reversal. 'Nodes of persisting complexity' are geographical locations which may experience lesser effects from 'de-complexification' due to having 'favourable starting conditions' that may allow the retention of a degree of complexity. A shortlist of nations (New Zealand, Iceland, the United Kingdom, Australia and Ireland) were identified and qualitatively analysed in detail to ascertain their potential to form 'nodes of persisting complexity' (New Zealand is identified as having the greatest potential). The analysis outputs are applied to identify insights for enhancing resilience to 'de-complexification'.

Keywords: sociopolitical complexity; collapse; de-complexification; lifeboats; carrying capacity; resilience

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Citation: King, N.; Jones, A. An Analysis of the Potential for the Formation of 'Nodes of Persisting Complexity'. *Sustainability* **2021**, *13*, 8161. https://doi.org/10.3390/su13158161

Academic Editor: JinHyo Joseph Yun

Received: 18 June 2021
Accepted: 19 July 2021
Published: 21 July 2021

1. Introduction

1.1. The Human and Earth System Predicament

The globe-spanning, energy-intensive industrial civilisation that characterises the modern era represents an anomalous situation when it is considered against the majority of human history. Several large revolutions in terms of population (total size and rate of change), social organisation and patterns of energy and other resource use have occurred to bring about the modern world. The first major change that humans achieved after a long period (approximately 3×10^5 years) of living in small, dispersed bands of hunter-gatherers was the transition to an agriculture-based civilisation, which occurred independently in multiple locations. This was enabled to a large degree by the shift approximately 1×10^4 years ago to a warmer, more stable interglacial climate at global scale that has been characterised as the Holocene [1].

The major shift resulting from the spread of agriculture led to consistent energetic and material surpluses which, in turn, allowed for the establishment of fixed urban settlements, hierarchal societies and organisational complexity such as labour specialisation. The emergence of these phenomena set in motion enhancing feedback mechanisms (e.g., food surpluses) that led to increasing populations and the spatial expansion of agriculture and human activity over the majority of the Earth [1]. The growth of the extent and complexity of human civilisation continued for centuries but was ultimately constrained by reliance on natural flows of energy (primarily insolation captured through photosynthesis and the availability of biomass in which it was stored) and the application of human/animal muscle power to utilise energy and material resources. Overcoming this limit commenced from approximately 1800 (the start of the Industrial Revolution) through the large-scale exploitation of the very large energy stock contained within fossil carbon deposits using newly developed technologies. This set in motion new enhancing feedbacks (e.g., coal-fired pumps which allowed previously inaccessible coal seams to be mined, providing further energy for industrial development) [1]. The global population and industrial capacity grew rapidly for approximately 150 years but achieved near-exponential growth only from approximately the middle of the 20th century. This period, characterised as the 'Great Acceleration' [2], has generated the most rapid and profound of all the changes described above, resulting from the strengthening of the feedbacks initiated at the start of the Industrial Revolution.

The 'Great Acceleration' is characterised by substantial and ongoing increases in societal complexity and the extent and intensity of human activities across a broad spectrum of measures including, but not limited to, population growth, energy and freshwater usage, nitrogen fixation and cement production. The aggregate effect of this dramatic growth has been the strong and increasing perturbation of the Earth system and the biosphere, making collective human civilisation a major force acting at global scale. This has led to the characterisation of recent Earth history as the 'Anthropocene' [2,3].

From a biophysical perspective, human civilisation is a non-equilibrium thermodynamic or dissipative system that must maintain a minimum level of available exergy to avoid entropic decay and a yet higher level to permit physical growth [4]. From the ecological economics perspective, it can be viewed as an 'economic superorganism' that seeks to maximise energy consumption through self-organisation at a large scale [1], or the 'megamachine' driven to ever greater size and scope by the enhancing feedbacks of capital accumulation [5].

The Earth System is, however, finite in spatial extent, energetic capacity and overall complexity, and the ongoing expansion of human endeavours has and will continue to result in the Earth System's limits being exceeded and the system being moved out of equilibrium. The Earth System (characterised as 'Gaia') is a self-regulating mechanism [6], and observable shifts in the behaviour of Earth Systems may be manifestations of balancing feedbacks resulting from the strong and growing perturbation from human activities. These may have the potential to fundamentally undermine the agriculture-based civilisation that has flourished in benign Holocene conditions.

The threats to the ongoing and future viability of globalised civilisation have been the subject of academics, popular science and literature at various points in history, but this subject area has garnered particular attention in recent years. The following subsections describe the most significant of these effects and why they might be significant for the predicament of human civilisation.

1.2. Literature Review of Global Environmental Threats

The following subsections describe four major categories of threats to the ongoing viability of the high-intensity civilisation that has emerged from the 'Great Acceleration'. These phenomena are the encountering of limits; diminishment of returns; ecological destruction; and 'risk multipliers'. These are discussed in detail in the following subsections.

1.2.1. Encountering of Limits

The 'Limits to Growth' studies [7,8] were seminal in that they first applied global scale modelling to human population, the industrial economy and global biophysical limits and identified the potential for future collapses of human population and welfare to occur. Recent re-analysis [9] suggests a strong correlation between the characteristics of worst-case modelling scenarios and real-world trends for the early 21st century. A recent calibration of the 'Limits to Growth' World3 model with real-world data (from 1995 to 2012) [10] identified some departures between the model and reality, although the broad findings held true. Despite the differing interpretation, the findings remain highly compelling and have inspired more recent work [11–13], which reapplied system dynamics models to the economy–environment system and identified the 'Seneca Effect', in which collapses might occur over short timescales.

Other attempts to describe the encountering of global-scale limits include the 'Planetary Boundaries' framework [14] which defines the Holocene's biophysical conditions in which civilisation developed and flourished as having boundaries for stability. Nine separate boundaries are defined, three of which (biodiversity loss, the nitrogen cycle and climate change) have been transgressed; further transgression may risk moving the Earth System to conditions inconducive to supporting large human populations. Another study [15] combined the socioeconomic Sustainable Development Goals (SDGs) with an integrated socioeconomic model of global human activity/biophysical model ('Earth3') to conclude that meeting the SDGs cannot be achieved within global environmental limits.

The studies described above consider the holistic, systemic viewpoint, but numerous studies also provide underpinning evidence for limit transgression with a narrower focus on resource depletion. The decline in production experienced [16] in multiple major oilfields worldwide and the low rate of discovery of large, new hydrocarbon sources in recent decades has significant implications for constraining key societal functions such as mass logistics. The peak use rates across multiple crucial resource types shows that numerous resources had a synchrony of peak use centred on the year 2006 [17]. The phenomenon has implications in terms of the capacity of global society to adapt to physical scarcity given that limits on the availability of multiple resources may have to be managed simultaneously, and this may constrain the capacity for substitution and 'de-coupling' of resource use [18].

1.2.2. Diminishment of Returns

Energy Return on Investment (EROI) [19,20] is a measure that has utility as a fundamental measure of the 'minimum energy' that is required to support continued economic activity and social function. Expanding on this [21,22], the availability of high EROI energy sources (that provide an 'excess' of energy) can be linked with socioeconomic complexity and 'higher' societal functions (e.g., education, health care, culture) that are indicative of higher living standards. 'Traditional' fossil fuels have provided a high EROI value for many decades, but the decline in the quality and accessibility (and therefore EROI) of these fuels, in parallel with the generally lower net energy provided by other energy sources, could result in a reduction in global economic output and quality of life [23–25]. This is supported by the MEDEAS model which indicates that a transition to an energy system with a high proportion of renewables may lead to an 'energy trap' [26]. Together, these studies indicate the crucial role of abundant, high EROI energy sources in maintaining societal functionality and growth, which contrasts with much of the extant economic worldview [27].

The 'excess' of energy provided by high-EROI energy resources has also provided the conditions for the enhancing feedback mechanisms of capital accumulation to permit the accumulation of wealth by sub-regions and -populations of the world. Evaluating [28] this phenomenon quantitatively through the application of predator–prey population dynamics models to assess the evolution of four factors ('elites/commoners/nature/wealth'), identifies that (economic) 'elites' preying on resources and the labour of 'commoners' can lead to economic stratification and ecological strain and, ultimately, irreversible societal collapse. Applying [29] qualitative arguments demonstrates that the affluent proportion of the human population have disproportionate global environmental impact (resource use and pollutant emissions), but cultural factors (wealth accumulation, consumerism, etc.) make the necessary changes to lifestyle unlikely to occur.

Sociopolitical complexity has been fundamental to the functioning and success of human societies post the Agricultural Revolution [28] and is described as the collective problem-solving and efficiency-seeking strategies deployed by all organised human societies in response to encountering problems, constraints (e.g., energy or water) or aspirations. It may include: 'bureaucracy' in the form of governments; specialisation of roles, occupations and industries; new technologies; and increased mobility and trade. The sociopolitical complexity [30] (hereafter complexity) provides marginal gains (i.e., net benefits) when initially deployed, but as further complexity is added, the marginal gains diminish in an inversely proportional manner. The subsequent progression through zero and then negative marginal benefit is posited as the factor consistent with societal collapses (in varied locations and timeframes) throughout history. Applying simple system dynamic models [31] ('mind sized'; [11]) demonstrates the tendency for complexity to peak and then diminish.

Modern, globalised civilisation is characterised by extreme levels of complexity, which has the potential to introduce additional risks. For example, nuclear technology [32] in the context of its development and the externalities (highly hazardous redundant facilities and long-lived waste that require highly controlled management) that it generates demonstrates the particular risk of such high-technology solutions in that they beget and 'lock in' the need for further complexity through the generation of egregious externalities. Any future reduction or loss of supporting complexity could result in widespread harm in the future if the persistent hazard that has been generated ceases to be manageable.

Modern complexity [33] (of the sociopolitical type, but also technological and informational) may have reached such levels as to have likely become largely and effectively indecipherable by individual humans, and human agencies and institutions. This may be manifesting in phenomena such as unpredictable behaviour in stock markets, frequent failures in the implementation of 'megaprojects' and the failure to address global-scale challenges.

1.2.3. Ecological Destruction

There are a total of five extinction events evident in the geological record which have been attributed to several natural events and causes (e.g., rapid climatic changes, flood basalt eruptions, bolide impacts) [34]. The sixth extinction episode (or alternatively, the Holocene Extinction Event) is currently ongoing [35], meaning that Earth's biosphere is currently under pressure at levels which occur only infrequently even over geological timescales. This "loss of biological diversity is one of the most severe human-caused global environmental problems" [35], particularly with the advent of the 'Great Acceleration'. The short timescale on which these impacts have grown, along with their sheer scope and extent, has resulted in <3% of the world's land surface area remaining as 'fundamentally intact', i.e., with species diversity and habitats unaffected by human activity [36].

The large-scale perturbation of ecosystems as the sixth extinction event progresses is likely to have severe global consequences, with the provision of vital 'ecosystem services' likely to severely reduce as effects cascade at global-scale [35]. The growth in human populations and technological development can be linked [37] to resource consumption, and the propensity for humans to destroy forest ecosystems gives a high probability (>90%) that global civilisation is very likely to suffer a catastrophic collapse in future (within a few decades). The current extinction event also differs in that it is driven by the concurrence of phenomena unique to human actions including changes in land and sea use; direct exploitation of animals and plants; climate change; pollution; and invasive alien species [38]. It is also characterised by unique Anthropocene features, such as the introduction of a global 'plastics cycle' [39], which pose an as-yet unknown threat to the stability of global ecosystems, and by extension, complex human civilisation.

1.2.4. Risk Multipliers

There are several phenomena which are emergent from the summation of human activities and the resultant perturbation of Earth Systems which serve as 'risk multipliers' that are likely to exacerbate existing trends and feedbacks. Climate change is likely to be the most pervasive of these risk multipliers, largely because the climatic system is planet-spanning and interfaces directly or indirectly with human and natural systems in highly complex ways. Climate change can be described as a 'hyperobject' [40], which are entities that have spatial and temporal scope and dimensions far beyond that of the human realm. The human system, when considered as an economic 'superorganism' [1,5] (a decentralised, energy-consuming structure that is emergent at global scale) may also be continuous with the 'climate hyperobject' given that it 'excretes' greenhouse gases.

The self-organising tendencies of these 'hyperobjects', which seek growth even where biophysical limits and environmental destruction constrain them, means that the prospects for reduction and reversal of greenhouse gas emissions are limited and accelerating feedback mechanisms [41] have the potential to exacerbate this tendency. It is possible to provide a qualitative framework [42] to identify which key underpinning societal functions are most likely to be subject to 'amplifying' effects, particularly in relation to conflict. Although the direct link between climate change and past and present conflicts is uncertain, there is support for the potential of climate change to introduce instabilities. It is within this context that climate change has been ascribed a near-certain potential to severely disrupt human civilisation [43], particularly in light of the potential for tipping points and non-linearities to occur within the climatic system [44].

Pandemics present another source of risk multiplication given their long history of strong feedbacks on human population dynamics and economic activity [13]. Several studies made prescient links between destructive human activities, such as deforestation, and pandemic risks, which have been borne out by the COVID-19 pandemic of the early 2020s [45–47]. The potential threat of coronaviruses [45] was known to pose a risk to human populations, particularly with bats as a vector (due to the nature of their virome). The political, economic, financial and social impacts of the COVID-19 pandemic are not yet understood given that it remains ongoing as of 2021 but are likely to be far-reaching and long-term given the broad-spectrum effects on various aspects of societies across the world. Furthermore, the United Nations [48] warns that future pandemics may be more severe than COVID-19 in terms of virulence, fatality rate and other impacts. The risk of infectious disease crossover due to ongoing human encroachment into remaining wild areas of the planet, combined with unpredictable societal impacts clearly demonstrates the cross-cutting risk presented by pandemics.

The risks arising from the extreme complexity and interconnectivity has developed as human society has grown and evolved through to the modern era [49,50]. Civilisation comprises an agglomeration of human and natural systems that interact in highly complex ways, and as such, there is an ever-growing probability that the smooth operation of the vital functions that underpin societies may be disrupted in the future. The increasing hyper-connectivity of the globalised economy [49] is a process characterised by the reduction in system resilience in favour of increased efficiency and complexity, which may increase the risk of initially small disturbances being subject to enhancing feedbacks that spread and potentially eventually create system-level threats (the 'Butterfly Defect'). An alternative viewpoint [50] is that complex, integrated societies have a natural resilience to a range of stresses and shocks, i.e., that they tend to self-correct when internal and external shocks occur (e.g., as seen in the response to the 'Global Financial Crisis'). However, perturbation in excess of 'tipping point' thresholds can create propagations leading to major changes in the state of such systems.

Whether the propagation of systemic risks is subject to threshold effects or has the potential to build from even minor disturbances, the risks of large-scale failures due to increasing globalisation, complexification, interdependency and the speed of fundamental societal support systems (particularly in the more developed regions of the world) creates significant global risks. This is particularly acute for the proportion of the human population that is entirely reliant on systems such as automated wastewater management and industrial food production (i.e., large urban populations). Furthermore, the global system may now have moved beyond human control or understanding [35] and may therefore be even more prone to catastrophic behaviour modes that can propagate in coupled systems through a range of unpredictable mechanisms [51]. This creates an interconnected global system that fails to adequately understand the nature of these complex, dynamic systems [52].

1.2.5. Societal Collapse

Overall, the literature sources summarised in the preceding subsections paint a picture of human civilisation that is in a perilous state, with large and growing risks developing in multiple spheres of the human endeavour. The synthesis of the conclusions presented in these myriad studies is that 70 years of the 'Great Acceleration' (plus the lesser but cumulative effects of the preceding approximate 10,000 years) have had indisputable, egregious effects on the functioning of the totality of the Earth System, and the continued trends and behaviours of the human collective look highly likely to exacerbate these existing trends. The potential for nonlinearities and other complex system effects only serve to potentially heighten the risks and consequences.

This can be summarised as [53] " . . . future environmental conditions will be far more dangerous than currently believed. The scale of the threats to the biosphere and all its lifeforms—including humanity—is in fact so great that it is difficult to grasp for even well-informed experts." This statement effectively sums up the current situation for humanity and indicates that it may be increasingly likely that the current (and near-future) timeframes represent a significant inflection point. Changes of varying magnitudes are possible in the coming years and decades, up to and including the collapse of organised societies. Various scientific and popular literature sources have explored the concept of societal collapse, with an increase in these descriptions occurring in recent decades as awareness and concern regarding the global environmental predicament has grown. Table 1 summarises the key features of the most significant of these conceptual descriptions.

Table 1. Summary of 'Collapse' Scenarios.

Nomenclature	Source(s)	Overview
Societal collapse	[7,8,28]	Significant and permanent decreases in measures including: human populations; stocks of non-renewable resources or representations such as 'wealth' or 'nature'; and other 'services' supporting civilisation.
Seneca cliff	[12,13]	Decease in measures (see above) that are characterised as occurring on a significantly more rapid timescale than their increase or build-up. A slow build-up of complexity followed by a very rapid 'de-complexification' (hence the 'cliff').
Olduvai collapse	[54]	Energy production per capita will undergo a peak and decline that will limit the overall duration of high technology, industrial civilisation. The collapse will be characterised by cascading failures of the electrical distribution systems that underpin civilisation and its support systems and cause a reversion to much simpler societies.
Overshoot and collapse	[55]	Complex systems commonly exhibit 'overshoot and collapse' dynamics in which exponential growth leads to depletion of supporting resources. This is mathematically and observationally demonstrable, e.g., through the behaviour of populations, resource extraction curves, etc.
Energy trap	[26]	This describes a global-scale situation in which increasing gross energy output delivers decreasing net energy to society. If gross energy consumption in such a scenario increases against a low or decreasing EROI value, there is potential for the triggering of the full collapse of the energy system.
Great Simplification	[1]	The large future reduction in global economic activity likely to occur to due to crucial limits being encountered. The limits most likely to cause this are availability of high EROI energy resources, and the effectiveness of debt as an instrument to 'pull resources forward' in time (i.e., financing the exploitation of resources with debt allows this to occur earlier, but with steeper future declines in the resource availability).
Power-down	[56]	Industrialised, globalised society is dependent on the continuous availability of high EROI energy resources (fossil hydrocarbons), and as availability of this declines, society will have less available energy to underpin its essential functions, and turmoil in the form of economic disruption, declining living standards and warfare may become likely.
The Contraction	[57]	The contraction is a hypothetical process described in fiction in which the period of global economic growth and globalisation (the 'Expansion' i.e., the Industrial Revolution and the 'Great Acceleration') would undergo a prolonged reversal (the 'Contraction') as crucial energy supplies (fossil fuels) become steadily scarcer.

1.2.6. Collapse Lifeboats

In line with the studies that have explored the concept of societal collapse, a number of studies in the scientific and popular literature have developed the concept of 'collapse lifeboats'. This generally describes locations that do not experience the most egregious effects of societal collapses (i.e., as may occur due to the effects of climatic changes) and are therefore able to maintain significant populations. These studies have considered small, isolated communities [58] in larger countries including Australia and New Zealand [54].

The concept is therefore an extrapolation of societal collapse, in that it considers events, features and societal structures that might feasibly develop in the context of a collapse.

Extrapolating the impact of warming due to climate change has been a particular focus for some of these studies. It is possible to explore the potential economic, social and ecological conditions prevailing in the world at each degree increase in the global average temperature due to climate change, from 1 to 6 °C. It is within the 5 °C increase scenario that the potential for major relocations to particular regions of the world can result in a reversal of globalisation [59], which in turn causes economic depression and shifts in global populations. The British Isles, Scandinavia, Patagonia, Tasmania and the South Island of New Zealand are identified as locations that migrants may seek to relocate to in this scenario. With the global average temperature increased by 4 °C, much of the land in the tropical and subtropical latitudes may become unproductive and depopulated, and inundated coastlines are common throughout the world [60] with Scandinavia, the British Isles and New Zealand identified as potential lifeboats. Using the perspective of the Gaia Hypothesis [6], northern Canada, Russia, Scandinavia, New Zealand and the British Isles (along with mountainous regions at lower latitudes) may remain habitable through the persistence of agriculture and may therefore act as 'lifeboats' for populations of humans.

Alternatively, a protracted 'energy descent' following the passing of peak oil, combined with the effects of climate change, can also lead to different future scenarios including 'Lifeboats' [61,62], which is a most pessimistic scenario, describing severe climatic changes combined with economic collapse leading to general decline in societal complexity, with isolated, localised pockets surviving as the indicated 'lifeboats', and is the most closely aligned with the scenario posited in this study. It may be possible to control a 'power down' of global society as a preferable pathway to that of economic and environmental collapse [56]. The 'power down' would comprise a concerted, global, long-term effort to reduce per capita energy and resource usage, equitably distribute resources and gradually decrease the global population including the possibility of 'Building Lifeboats' through community solidarity and preservation.

1.3. 'De-Complexification' and 'Nodes of Persisting Complexity'

1.3.1. 'De-Complexification'

A robust assumption based on historical events and behaviours [28,30] is that future changes may reduce or reverse certain fundamental measures of the condition of global civilisation, including (but not limited to) total energy and resource use, systemic interconnectedness and rate of economic growth. The terminology of (sociopolitical, societal and technological) complexity [30,31] is a useful framing that summarises the collective state of global human civilisation and allows the definition of a concept labelled as 'de-complexification'.

'De-complexification' is defined as a condition in which the overall complexity of human societies at global scale would undergo a large and broad-spectrum (i.e., affecting all parts of societies, technological systems and environments) reduction. Although this concept is central to this study, it is not defined in detailed terms, nor is it quantified. Instead, it is applied as a generalised description that captures a slowdown, cessation or reversal of the trends that are characteristic of recent civilisation, notably, the exponential increases in multiple parameters, i.e., the 'Great Acceleration' [2].

At the highest level, the cause underlying such a 'de-complexification' is the nexus of trends and phenomena described in Section 1.2. It is not possible to be more specific about the cause(s) that could potentially result in this occurring, but some possible modes of behaviour for its occurrence can be described in more general terms. 'De-complexification' could feasibly occur as a discrete, short duration event [12,13]; as a more prolonged, gradual and long-term process [63]; or potentially as a hybrid of both these types of events. These are described in more detail below:

- 'Seneca type'—this would likely result from a discrete initiation event or phase for which there are no significant signals of the coming disruption and would lead to a

rapid and profound 'de-complexification' (potentially on the order of <1 year–years timescales) [12,13].
- 'Long descent type'—this would likely result from a combination of factors over a longer time period, and so would not be attributable to a singular initiation event and would likely be more gradual and incremental in nature (potentially on the order of years–decades timescales) [63].
- A 'hybrid' of these might be 'de-complexification' with a prolonged, gradual and non-discrete initiation but which accelerates through the emergence of factors that gain a 'momentum' through gradually strengthening enhancing feedback mechanisms and/or cascading events, leading eventually to an abrupt 'Seneca type' event that results in the loss of remaining complexity.

Any 'de-complexification process', whether abrupt in duration or as a result of a more prolonged reduction, would likely be heterogeneous in its progression. Neither the nature of any such changes, nor the behaviour of human and natural systems during any such period of disruption can be predicted at any spatial or temporal resolution, but some broad assumptions about possible system behaviours and end states can be considered. The severity and consequences of this reduction would be highly dependent on multiple complex factors such as the exact starting conditions at the initiation of 'de-complexification'. This process can, however, generally be assumed to result in significant changes to the fundamental extant organising principles of global societies and, likely, the greatly reduced availability of energy and resources, systemic interconnectivity, mobility and size and distribution of populations (i.e., up to the severe 'catastrophe trajectories' [64]).

1.3.2. 'Nodes of Persisting Complexity'

Building on 'de-complexification', this study introduces the concept of the 'node of persisting complexity' as a distinct alternative to the 'lifeboats' concept. This is of importance because the term 'lifeboat' has the potential for controversy and to be politically charged due to potential for links with narratives related to future immigration controls and nationalism. This study instead seeks to explore possible and likely (qualitative) system behaviour arising from a global 'de-complexification' event.

This will be based on a consideration of what geographical locations (nations) may retain some level of complexity (i.e., an appreciable fraction of current levels) during and after a 'de-complexification' event (i.e., to become 'nodes of persisting complexity'). This will require that several different characteristics and factors (labelled as 'favourable starting conditions') be considered in conjunction, in order to identify the areas that have the highest likelihood of retaining complexity during the course of a global evolution to an overall less complex state. It is noted that the nature of complex systems means that the final system states (i.e., after a global 'de-complexification' event) cannot be predicted with any degree of certainty or granularity. However, the initial starting conditions can have a significant influence on final system states, so 'favourable starting conditions' are considered to be a reasonable metric for this study.

The central underpinning concept of this study therefore differs from the conjecture in other studies that certain locations may be 'preserved' as lifeboats through deliberate action (i.e., by governments or other groups). Instead, the formation of any 'node of persisting complexity' would be through system behaviour arising from certain starting conditions, i.e., is an analysis of an evolutionary process that would occur largely outside of direct human control. This description has some similarities with the 'Regenerative Bioregions' concept [65] in which future localised populations may persist through their overall biophysical demands matching regional ecological conditions and carrying capacities.

2. Materials and Methods

2.1. Aim and Objective

The aim of this study is to identify a shortlist of nations that have natural and anthropogenic 'favourable starting conditions' such that they may have a propensity to form 'nodes of persisting complexity' in a hypothetical future global 'de-complexification' event. The objectives are to:

- Define and apply a simple semi-quantitative methodology to screen an existing dataset of nations in order to generate a 'shortlist' of the strongest candidates in terms of their 'favourable starting conditions';
- Undertake an initial qualitative analysis of each these 'shortlist' nations in order to characterise their unique features and analyse their potential to form a 'node of persisting complexity'; and
- Analyse the features identified to ascertain what features and characteristics may be applicable in the contemporary world to increase the resilience of nations (and other geographical regions) that do not currently have 'favourable starting conditions'.

2.2. Approach

As noted above, the first objective of this analysis is to define and underpin a 'shortlist' of nations which have inherent natural and anthropogenic characteristics that in combination are likely to comprise 'favourable starting conditions'. This shortlist will need to take account of the factors that are of the greatest relevance to the potential nature of a 'de-complexification' event to identify which conditions may interact with such an event to give a higher probability of allowing a degree of complexity to persist.

The methodology for the identification of 'shortlisted' nations is based around the extrapolation and further analysis of the outputs of the 'University of Notre Dame—Global Adaptation Index' (ND-GAIN) [66] study. This is a study that considers a range of factors relating to the potential for climate change to disrupt different nations around the world. It gathers and processes a range of different variables to generate indicators of vulnerability to climate disruptions and readiness to mobilise adaptive actions. The overall output of the study is a combined score for each nation in the world and a ranking of nations according to proneness to climate change. Table A1 in Appendix A outlines the ranking of the highest-scoring nations, and Tables A2 and A3 (in Appendices B and C, respectively) list the 45 indicators used in the calculation of the ND-GAIN Index.

The study is considered to be comprehensive, robust and the data is open access, so it provides a strong basis for the analysis undertaken in this study. However, it does not account for several factors which are specific to the analysis of 'favourable starting conditions/nodes of persisting complexity'. Therefore, additional semi-quantitative screening is applied to the top 20 least vulnerable nations [66] to generate a final 'shortlist' of five nations using three additional analytical measures that pertain specifically to the 'de-complexification' scenario. For each of these three measures, an analysis is undertaken based on a semi-quantitative scoring system that is combined with the ranking provided by ND-GAIN to produce a 'shortlist' of five nations with the highest 'favourable starting condition' rating. These nations are then taken forward to the next stage of more detailed qualitative analysis (in Section 4). Table 2 describes the additional analytical measures and the basis for the 'scoring' applied.

Table 2. Additional Measures for Assessment of 'De-complexification'.

Name	Description and Basis of Scoring	
Carrying Capacity Analysis	This analysis considers nations from the purely biophysical perspective of whether the extent of arable land within the borders of a country could provide sufficient food to support the current population (assuming that large-scale food imports would be inaccessible under a hypothetical future 'de-complexification' event), i.e., is the current population in excess of the land's carrying capacity. The arable land per capita (calculated and presented in Appendix D) is compared with the land area required to provide at least a subsistence diet to assign a semi-quantitative score as follows:	
	1	The land area available per capita is negligible or significantly below the minimum subsistence level.
	2	The land area available per capita is below the minimum subsistence level.
	3	The land area available per capita is broadly commensurate with the minimum subsistence level.
	4	The land area available per capita is above the minimum subsistence level.
	5	The land area available per capita is significantly above the minimum subsistence level.
Isolation Analysis	This is primarily defined on the basis of connection and proximity to large external populations (e.g., megacities, regional population centres) that may be subject to significant population displacement and geographical features that may make the subject country/region a favoured location for large-scale migrations. It is related to the Carrying Capacity Analysis in that any displacement of populations would adversely affect the ratio of population to carrying capacity in the receiving destination. A score is assigned on the basis of a subjective, general analysis of the geographical situation of the nation in question as follows:	
	1	The nation is directly connected by land or narrow straits to and/or has close proximity to external population centres.
	2	The nation has moderate land or sea connections and/or has moderate proximity to external population centres.
	3	The nation has longer land or sea connections and/or has moderate proximity to external population centres, but other factors (e.g., high latitude) increase relative isolation.
	4	The nation has moderate separation and/or distance from external population centres.
	5	The nation has a large separation and/or distance from external population centres.
Self-sufficiency Analysis	It is noted that this is one of the metrics accounted for in ND-GAIN, but the emphasis in that study is on energy imports and general manufacturing capacity. This metric is concerned with how self-sufficient nations may be under a hypothetical future 'de-complexification' event, i.e., how a particular country may be able to respond to the disruption, shrinkage or cessation of global supply lines through its access to and flexibility of indigenous energy supplies and manufacturing capacity. A score is assigned on the basis of a subjective, general analysis of the energy and manufacturing infrastructure and capacity of the nation in question as follows:	
	1	The nation has negligible or very limited existing indigenous renewable energy resources and/or manufacturing capacity.
	2	The nation has limited existing indigenous renewable energy resources and/or manufacturing capacity.
	3	The nation has moderate existing indigenous renewable energy resources and/or manufacturing capacity.
	4	The nation has significant existing indigenous renewable energy resources and/or manufacturing capacity.
	5	The nation has very significant existing indigenous renewable energy resources and/or manufacturing capacity.

Notes: It is acknowledged that 'carrying capacity' is not a firmly defined concept; [67] describes it as a complex, non-constant phenomenon that emerges from processes and interdependent relationships between limited resources and the populations that depend on them. For the purposes of this paper, carrying capacity is assumed to be a simple measure of the human population that can be sustained by the theoretical maximum extent of agricultural land within a given nation, i.e., the assessment of agricultural land available per capita. Ref. [68] notes that the average global land demand is 2.2 hectares (0.022 km^2) per capita, but this is based on total ecological footprint to support a range of lifestyles from subsistence through to industrialised Western lifestyles, i.e., this accounts for food, fibre, pollution absorption, etc. The estimated land area required to sustain one person at an adequate level of calories with a vegetarian diet ranges from 0.0001 km^2 [69] to 0.002 km^2 [70].

The semi-quantitative/subjective nature of the three further analytical factors means that a scoring scale with only five gradations (i.e., which is reasonably imprecise and approximate) is deemed to be appropriate. This first stage of the further analysis is intended to be a general appraisal of the situation of a given nation, and the summation of the scores for these additional analytical measures (in combination with their ND-GAIN rating) is intended to 'draw out' a shortlist of those nations with generally greater 'favourable starting conditions'.

It is noted and acknowledged that the analysis applied is here is simple and superficial in nature and does not attempt to apply a rigorous analysis using a range of quantifiable variables; this approach is deemed to be appropriate for the analysis being attempted here. This is primarily because the 'nodes of persisting complexity' that this study postulates are proposed to form through evolutionary complex system behaviour (i.e., partially or largely outside direct human control rather than as a direct result of human action and agency). Such systemic behaviour is inherently highly complex and unpredictable and dependent on a large number of interconnected variables. Therefore, a detailed analysis that attempts to make statistical or other predictions of system behaviour would not be robust or could only be attempted using multi-parameter modelling approaches such as system dynamics (which, even if built to account for a large number of variables, would likely only be able to make estimates of broad 'modes' of system behaviour, which is what this analysis does). Therefore, a simpler, high-level approach that makes a 'low-resolution' analysis of key features is proportionate for making a very macro-scale, low-resolution (i.e., at global and national scale) assessment and offers a robust basis for further qualitative analysis of potential 'nodes of persisting complexity'.

3. Results

The application of the scoring mechanism outlined in Section 2.2 (along with information underpinning this analysis) to the top 20 'least vulnerable' nations (as identified by ND-GAIN [66]) is presented in Table 3. This identifies the five nations with the most significant 'favourable starting conditions', which are then taken forward for more detailed, individual discussion in Section 4.

Table 3. Scoring and Underpinning of Assessment of 'De-complexification'.

Country	Carrying Capacity Analysis (Refer to Table A4 in Appendix D for Supporting Calculations)	Isolation Analysis	Self-Sufficiency Analysis	Total
Norway	2 Low current population; 5.5 million [71] but very low fraction of agricultural land; 2.7% [72] means that agricultural land per capita is low at 0.002 km^2. Direct access to the North Atlantic and Arctic Oceans.	3 Direct land connection to the Eurasian landmass but high northern latitude means it is remote from large European population centres.	4 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	9
New Zealand	5 Low current population; 5.0 million [71] and high fraction of agricultural land; 43.2% [72] means that agricultural land per capita is high at 0.023 km^2. Direct access to the Pacific and Southern Oceans.	5 Island archipelago in the southwestern Pacific Ocean at mid southern latitudes with no nearby large or heavily populated landmasses	3 Abundant indigenous renewable energy sources. Modern economy but predominantly primary-resource-based, limited manufacturing capacity.	13
Finland	2 Low current population; 5.6 million [71] but low fraction of agricultural land; 7.5% [72] means that agricultural land per capita is low at 0.004 km^2. Direct access to the Baltic Sea.	3 Direct land connection to the Eurasian landmass, but high northern latitude means it is remote from large European population centres.	3 Moderate indigenous renewable and non-renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	8
Denmark	3 Low current population; 5.9 million [71] high fraction of agricultural land; 63.4% [72] but small total land area means that agricultural land per capita is low at 0.005 km^2. Direct access to Baltic and North Seas.	2 In close proximity to large European population centres.	3 Abundant indigenous renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	8
Sweden	2 Moderate current population; 10.3 million [71] but low fraction of agricultural land; 7.5% [72] means that agricultural land per capita is low at 0.003 km^2. Direct access to the Baltic and North Seas.	3 Direct land connection to the Eurasian landmass but high northern latitude means it is moderately remote from large European population centres.	3 Abundant indigenous renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	8
Switzerland	2 Low current population; 8.5 million [71] high fraction of agricultural land; 38.7% [72] but small total land area means that agricultural land per capita is low at 0.002 km^2. Landlocked country.	1 Centrally located within large European population centres.	3 Moderate indigenous renewable and non-renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	6

Table 3. *Cont.*

Country	Carrying Capacity Analysis (Refer to Table A4 in Appendix D for Supporting Calculations)	Isolation Analysis	Self-Sufficiency Analysis	Total
Singapore	1 Low current population; 5.9 million [71], but very low fraction of agricultural land; 1% [72] and very small total land area means that agricultural land per capita is negligible. Direct access to the Indian Ocean and South China Sea.	1 Island city-state separated from the Eurasian landmass by a narrow strait, centrally located within large Asian population centres.	2 Very limited indigenous renewable and non-renewable energy sources. Modern high-tech economy with limited manufacturing capacity.	4
Austria	2 Low current population; 8.9 million; [71] high fraction of agricultural land; 38.4% [72] but small total land area means that agricultural land per capita is low at 0.004 km^2. Landlocked country.	1 Centrally located within large European population centres.	3 Abundant indigenous renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	6
Iceland	4 Very low current population; 354,000 [71] and moderate fraction of agricultural land; 18.7% [72] means that agricultural land per capita is moderate at 0.053 km^2. Direct access to the North Atlantic Ocean.	5 Island in the North Atlantic Ocean at high northern latitudes with no nearby large or heavily populated landmasses	2 Abundant indigenous renewable energy sources. Modern high-tech economy with limited manufacturing capacity.	11
Germany	2 High current population; 79.9 million [71] high fraction of agricultural land; 48% [72] but moderate total land area means that agricultural land per capita is low at 0.002 km^2. Direct access to the Baltic and North Seas.	1 Centrally located within large European population centres.	5 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with very large manufacturing capacity.	8
United Kingdom	3 High current population; 66.1 million [71] very high fraction of agricultural land; 71% [72] but moderate total land area means that agricultural land per capita is low at 0.003 km^2. Direct access to the North Atlantic Ocean and North Sea.	4 Island in the northeastern Atlantic Ocean at mid-high northern latitudes, separated from the Eurasian landmass by a moderately sized strait, peripheral to large European population centres.	4 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with large manufacturing capacity.	11
Luxembourg	1 Very low current population; 640,000 [71] high fraction of agricultural land; 51% [72] but very low total land area means that agricultural land per capita is low at 0.002 km^2. Landlocked country.	1 Centrally located within large European population centres.	2 Very limited indigenous renewable and non-renewable energy sources. Modern high-tech economy with very limited manufacturing capacity.	4

Table 3. *Cont.*

Country	Carrying Capacity Analysis (Refer to Table A4 in Appendix D for Supporting Calculations)	Isolation Analysis	Self-Sufficiency Analysis	Total
Australia	5 Moderate current population; 25.8 million [71], high fraction of agricultural land; 52.9% [72] and very large total land areas means that agricultural land per capita is very high at 0.158 km^2. Direct access to the Pacific and Indian Oceans.	4 Island continent located between the Pacific, Southern and Indian Oceans at low-mid southern latitudes, separated from outlying islands of the Eurasian landmass by a moderately-sized strait, peripheral to large Asian population centres.	4 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	13
Korea	1 High current population; 51.7 million [71] moderate fraction of agricultural land; 18.1% [72] and moderate total land area means that agricultural land per capita is negligible. Direct access to the Sea of Japan and East China Sea.	2 Direct land connection to the Eurasian landmass in close proximity to large Asian population centres.	3 Moderate indigenous renewable and non-renewable energy sources. Modern high-tech economy with very large manufacturing capacity.	6
Japan	1 Very high current population; 124.7 million [71] and low fraction of agricultural land; 12.5% [72] means that agricultural land per capita is negligible. Direct access to the Pacific Ocean and Sea of Japan.	3 Island archipelago in the northwestern Pacific Ocean at low-mid northern latitudes, separated from Eurasian landmass by a moderately-sized sea, peripheral to large Asian population centres.	4 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with very large manufacturing capacity.	8
The Netherlands	2 High current population; 17.3 million [71] high fraction of agricultural land; 55.1% [72] but low total land area means that agricultural land per capita is very low at 0.001 km^2. Direct access to the North Sea.	1 Centrally located within large European population centres.	3 Moderate indigenous renewable and non-renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	6
France	3 High current population; 68.1 million [71] but high fraction of agricultural land; 52.7% [72] means that agricultural land per capita is moderate at 0.004 km^2. Direct access to the North Atlantic Ocean.	1 Centrally located within large European population centres.	4 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with large manufacturing capacity.	8
Canada	4 Moderate current population; 37.9 million [71] low fraction of agricultural land; 6.8% [72] but very large total land area means that agricultural land per capita is moderate at 0.016 km^2. Direct access to the Pacific and North Atlantic Oceans.	2 Direct land connection to the North and Central American landmass; in close proximity to large North American population centres.	4 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with moderate manufacturing capacity.	10

Table 3. *Cont.*

Country	Carrying Capacity Analysis (Refer to Table A4 in Appendix D for Supporting Calculations)	Isolation Analysis	Self-Sufficiency Analysis	Total
United States	4 Very high current population; 335.0 million [71] high fraction of agricultural land; 44.5% [72] and very large total land area means that agricultural land per capita is moderate at 0.012 km^2. Direct access to the Pacific and North Atlantic Oceans.	1 Centrally located within large North and Central American population centres.	5 Abundant indigenous renewable and non-renewable energy sources. Modern high-tech economy with very large manufacturing capacity.	10
Ireland	5 Low current population; 5.2 million [71] and very high fraction of agricultural land; 66.1% [72] means that agricultural land per capita is moderate at 0.009 km^2. Direct access to the North Atlantic Ocean.	5 Island in the northeastern Atlantic Ocean at mid-high northern latitudes, separated from Eurasian landmass by the Island of Britain, a sea and a moderately sized strait, remote from large European population centres.	2 Moderate indigenous renewable energy sources. Modern economy but predominantly primary-resource-based; limited manufacturing capacity.	12

Notes: 'Agricultural land' is total area of land utilised for all forms of agriculture, including arable, permanent cropland and permanent pasture [72]. Note that for some countries (e.g., Australia) pasture may make up a large proportion of the total, so a large fraction of the land in question may not comprise highly fertile land capable of high-productivity output that could support large human populations. Therefore, the metric of 'fraction of agricultural land' is used as an indicative measure of the general carrying capacity of the territory of the country in question but may not reflect the country's true capacity for food production.

Table 4 shows the calculation for the ‘favourable starting conditions’ rating for all of the nations that scored >10 (note not inclusive) i.e., those with the ‘favourable starting conditions’ for the potential formation of ‘nodes of persisting complexity.

Table 4. ‘Favourable Starting Location’ Rating.

Country	Further Analysis Score [A]	ND-Gain Ranking [B]	‘Favourable Starting Condition’ Rating [A/B]
New Zealand	13	2	6.5
Iceland	11	9	1.2
United Kingdom	11	11	1
Australia	13	13	1
Ireland	12	20	0.6

4. Discussion

The crucial features common to the nations that scored >10 in the ‘further analysis’ (and therefore having ‘favourable starting conditions’) are that they consist of islands, island archipelagos or island continents located at temperate latitudes with strong Oceanic climatic influence. We note that Iceland is located at sub-polar latitudes but has a climate buffered by the North Atlantic Gulf Stream/North Atlantic Current and so has characteristics of a landmass located further south and Australia encompasses multiple climatic regimes due to its physical size, but includes a significant area with a temperate Oceanic climate, principally the island/State of Tasmania (refer to Section 4.1). Nations and geographical regions with these climatic characteristics have a relatively low degree of temperature and precipitation variability currently and therefore would remain this way at the start of any ‘de-complexification’ process. These locations would therefore also have the greatest likelihood of relatively stable conditions being buffered and persisting in response to climate change scenarios for the 21st century.

By contrast, geographical regions in the tropics and subtropics are likely to suffer some of the largest changes in climatic patterns and at the earliest stages of projected climate change [73–75]. The continued viability of large-scale agriculture is more likely in any regions with existing areas of rain-fed, high-quality and fertile soil that is at lower risk of erosion and degradation due to the buffering of potentially warmer, stormier and more generally unstable future climatic conditions. Alongside agriculture, access to domestic sources of energy is required to support the continuation of fundamental societal functions and therefore support the formation of ‘nodes of persisting complexity’. For example, renewable electricity generation capacity could permit the ongoing operation of crucial infrastructure (e.g., communications networks, pumping and treatment of water for irrigation and supply and manufacturing capacity) that would be necessary to support key capabilities.

It is noted that highly complex technological systems such as power grids are reliant on technical knowledge and physical components, the provision of which is at least in part via highly specialised manufacturing and globalised supply chains (which is a key vulnerability [76]). In the event of a failure of these systems at global scale due to a ‘de-complexification’ event, the viability of the ongoing operation of large electrical systems exploiting renewable energy systems or the development new sources (e.g., drilling new deep hydrothermal wells) could potentially be in doubt. For the purposes of this analysis, it is assumed that grids could be maintained at some level of functionality through domestic manufacturing capacity. We also assume that other import dependencies of domestic industries including fertilizer or farm machinery can be discounted by assuming that a sustainable intensification of agriculture would be adopted in the event of a de-complexification event, or substitutions of key resources would be possible.

The nations discussed in the following subsections are currently net importers of liquid hydrocarbon fuels for transport (and other) purposes (e.g., as described by [77] in the case of Iceland) either because they do not have significant indigenous liquid hydrocarbon reserves (Iceland, Australia, Ireland) or have substantially depleted their reserves (New

Zealand, United Kingdom). The technologies to use renewable (or nuclear) electricity to generate synthetic liquid fuels have been developed but have not yet been deployed at scale [78], so it is assumed that this technology would also not be available following a 'de-complexification' event.

The following discussions therefore disregard the use of large volumes of liquid fuels for purposes, such as mass road transportation and aviation, and other primary fuels for large-scale industrial applications, such as cement manufacture. This assumes that in a global 'de-complexification' event, large-scale mobility within and between nations, and the impetus for ongoing mass production of certain commodities, would reduce significantly. Electrical energy at either national or more local scales for essential functions as outlined above are instead assumed to be the priority.

4.1. Discussion by Nation

Table 5 contains further detailed analyses of each of the five nations identified in Table 4. For each nation, the analysis is divided into the following: energy resources; climate, agricultural resources and other factors; and an overview of the national situation with regards to potential for formation of 'nodes of persisting complexity' (the information is presented in bulleted format for ease of presentation and comprehension).

Table 5. Further Analysis by Nation.

Nation		Discussion
New Zealand	Energy Resources	• Abundant domestic renewable energy resources, with existing large-scale utilisation of geothermal and hydroelectric resources. • The national geothermal resource is currently partially exploited, with potential for significant future increases in usage: ○ Currently, 740 MW of shallow geothermal energy is developed in the North Island Taupo Volcanic Zone (TVZ) [79]; exploitation of deeper geothermal resources may yield further large energy resources. ○ In addition to the TVZ, there is potential for development of shallow geothermal resources [80] on the Alpine Fault on the South Island • The national hydroelectric resource is currently extensively exploited: ○ The Manapouri hydroelectric scheme/Tiwai Point Aluminium Smelter in the far south of the South Island were co-developed with the infrastructure configured specifically to supply the energy demands of the smelting operations [81]. ○ The likely future closure of the smelter for economic reasons [82] means that approximate 800 MW output of the Manapouri Power Station may become 'surplus' in future and could become available for more general national use. • There is also a large and only partially developed potential for solar and on/offshore wind energy generation.
	Climate, Agricultural resources and other factors	• New Zealand has a temperate, oceanic climate with abundant precipitation (with regional variation, e.g., sub-tropical zones in the north [83]). • There is also abundant agricultural land (and a high per capita availability, as identified in Table 4). However, [84] identifies the challenges associated with access to water resources, particularly in relation to heterogeneous distribution and decreasing quality due to widespread contemporary agricultural over-intensity (noting that access to energy resources could contribute to alleviating challenges such as these). • New Zealand also has susceptibility/vulnerability to natural hazards (particularly geohazards such as large seismic and/or volcanic events).
	Overview	• In terms of provision of indigenous electrical energy, New Zealand has highly favourable conditions as a result of its geographic contexts (a volcanically and tectonically active archipelago). • The potential future general availability of the output of the Manapouri scheme may result in New Zealand in essence having more energy than it can use, even before development of future resources is considered. • Despite abundant energy resources, manufacturing capacity has historically been limited. • This is, however, largely a function of a historical/current low population density, remoteness from world markets and a reliance on agriculture as an economic mainstay. • Overall, New Zealand has inherent, specific features that make it a compelling candidate as a potential 'node of persisting complexity'.

Table 5. *Cont.*

Nation		**Discussion**
Iceland	Energy Resources	• Abundant domestic renewable energy resources, with existing large-scale utilisation of geothermal and hydroelectric resources ○ The national geothermal resource has already been extensively developed (utilised for electrical generation and widespread urban space heating) [77,85]. • The national hydroelectric resource is currently partially exploited: ○ The key component of Iceland's hydroelectric generation infrastructure is the 690MW Kárahnjúkar hydroelectric plant [86]. This was commissioned in 2007 to supply power to the Aluminium smelter in Fjardaál (through a dedicated transmission line) and is Iceland's largest power station (accounting for approx. 25% of the nation's generation capacity). • There is also a large and currently undeveloped potential for solar (which is significant even with the low solar irradiance values received at Iceland's high latitude) and on/offshore wind energy generation.
	Climate, Agricultural resources and other factors	• Iceland has a cool temperate climate (the island is at sub-Arctic latitude, but the climatic regime is moderated by the North Atlantic Current) with moderate precipitation [83] ○ It has a high per capita availability of agricultural land; this is, however, largely an artefact of the very low population of the country relative to its total geographical area. • Although the total fraction of agricultural land is moderate [72], there is limited agricultural capacity [87] (due to limited fertile land and a climate unsuited to many arable crops) and remains reliant on food imports for a large proportion of its domestic demand. • Iceland is also prone (in a similar manner to New Zealand) to volcanic geohazards, which pose an ongoing threat to the agricultural resources that the nation does possess. • The low provision of land suitable for arable or livestock farming is, however, partly offset by extensive and well-established fisheries in the surrounding North Atlantic and the increasing use of intensive agricultural techniques supplemented by technology and abundant energy availability (e.g., geothermally heated polytunnels).
	Overview	• In terms of provision of indigenous electrical energy, Iceland has highly favourable conditions as a result of its geographic contexts (a volcanically active island at high northern latitudes, resulting in icecaps with significant runoff). • These indigenous sources comprise a resource that is greater than national demand (particularly if the requirements of Fjardaál were subtracted) in a similar vein to New Zealand. • Overall, Iceland has several 'favourable starting conditions' (primarily an abundance of current/potential renewable energy resources that may serve to offset agricultural capacity limited by geography) that give it potential to comprise a future 'node of persisting complexity'.

Table 5. *Cont.*

Nation		Discussion
United Kingdom	Energy Resources	● The United Kingdom has mixed energy resources and capacity [88] and, therefore, a more complex ‘energy base’ than the other nations considered to have ‘favourable starting conditions’. ● It currently has a large (but decreasing) reliance of fossil fuel (particularly natural gas) and nuclear generation capacity, with a large (and increasing—peaking at up to approx. 50% of total electrical load) renewables contribution (particularly offshore wind). ● The indigenous renewable energy infrastructure also has significant potential to be increased, primarily due to currently unexploited wind resources, but also through infrastructure to exploit other large resources, such as lagoons or barrages in the highly tidal Severn Estuary [89].
	Climate, Agricultural resources and other factors	● The United Kingdom has a temperate climate (moderated by prevailing southwest winds over the North Atlantic Current), plentiful precipitation [83] and generally fertile soils. ● It has a low per capita availability of agricultural land; this is, however, largely an artefact of the very high population of the country relative to its endowment of agricultural land and total geographical area. ● Agriculture in the United Kingdom is extensive [90], varied in terms of produce and outputs and shows generally increasing trends in outputs and generally improving environmental metrics. ● The United Kingdom is not prone to major natural hazards, though extreme weather events have the potential to damage agricultural output, particularly considering the small land area of the nation.
	Overview	● The United Kingdom has an overall complex and mixed picture for ‘favourable starting conditions’. ● It has extensive renewable energy resources (primarily wind), which are partially exploited and with capacity for the usage to increase in future. ○ However, it has a high population and per capita energy demand [91], and meeting contemporary demands with renewables alone would require very extensive infrastructure, hence the lower penetration than other nations considered ○ The reliance on a mix of generation sources also has the potential to render a transition in a global ‘de-complexification’ event more challenging. High-technology generation sources that rely on globalised supply chains for fuel and other support services (i.e., natural gas and nuclear generation capacity) could potentially be rendered at least partly inoperable after a period of time (although the nation’s manufacturing capabilities may be able to at least partly mitigate this). ○ A switch to greater reliance on renewables could also be more challenging than in the nations that currently have a simpler energy mix with much higher existing penetration of renewables, even with decreased energy demand. ● The issues with energy and agricultural resources are compounded by the large population and small land area; these factors limit the potential for this nation to comprise a future ‘node of persisting complexity’.

Table 5. *Cont.*

Nation		Discussion
Australia	Energy Resources	• Focusing on Tasmania (see below), the island has a significant endowment of renewable energy, primarily in the form of hydroelectric capacity (comprising a smaller number of large power stations and a larger number of small to medium generators) and wind generation capacity. ○ There is also a large and currently undeveloped potential for expansion of renewable generation capacity, which is being explored through the 'Battery for the Nation' initiative [92].
	Climate, Agricultural resources and other factors	• The continental scale of Australia means that it encompasses large variations in climate, but the majority of the landmass experiences arid to semi-arid conditions, with wet tropical conditions prevailing in the far north and temperate conditions prevailing in the southeast of the continent and Tasmania [83]. • Land use is dominated by agriculture in the temperate, higher precipitation zones and rangeland in the drier central and northern zones. • In the case of Tasmania, one-quarter of the landmass is currently in use for agriculture [93], and the (relatively, by the standards of Australia) fertile soil and temperate, oceanic climate allow for varied and productive agriculture.
	Overview	• Climatic warming [94] is likely to lead to the exacerbation of existing trends on the Australian continent, i.e., increased precipitation in wet, tropical zones and decreased precipitation in temperate and arid zones (i.e., prevailing climatic conditions that are likely to be become more extreme), which is likely to result in generalised negative effects for biodiversity, agriculture and infrastructure. • Land use patterns introduced since European colonisation of the continent have degraded the (already low fertility) land such that the impacts of climate change (incidences of wildfires, water shortages) are likely be exacerbated. • Australia presents a unique situation amongst the other nations in that an enclave (the island State of Tasmania) diverges significantly from the continental landmass by a number of measures. ○ Ref. [95] describes the general climatic changes that have occurred to date in Tasmania, and the conditions that are likely to prevail over the course of the 21st century due to climate change; temperatures in Tasmania have increased since the mid-20th century but to a lesser extent than in continental Australia, but total rainfall has decreased in line with that experience in southern Australia. ○ Under high or low global emissions scenarios, temperature increases in Tasmania are projected to be lower than the global average, largely due to a southerly latitude and the moderating influence of the Southern Ocean, though the spatial and seasonal distribution of precipitation is likely to undergo significant change due to climatic changes. • Overall, Tasmania is likely to experience lesser climate change impacts than continental Australia, and as such, may act as a localised region of that nation with greater 'favourable starting conditions', and could become increasingly recognised as Australia's 'local refuge (lifeboat)' as conditions on the continental mainland may become less amenable to supporting large human populations in the future.

Table 5. *Cont.*

Nation		Discussion
Ireland	Energy Resources	● The island of Ireland (disregarding political subdivisions) is somewhat similar to the UK in terms of majority reliance on natural gas-fired thermal generation, but with a significant and rapidly growing contribution from renewables, which has the potential to improve energy security overall [85]. ○ Approximately one-quarter of electricity generation was from renewable sources (predominantly wind generation, but renewable gas and hydroelectric as well) in 2019, which represented a 13% increase over the previous year. There is potential to grow this capacity through use of currently unexploited offshore wind resources [96]. ● Key differences from the United Kingdom are a much smaller population and therefore a much smaller overall energy demand, and the absence of nuclear generation capacity. The lower energy demand combined with the absence of partial reliance on high-technology energy sources means that a transition to reliance on renewables (assuming drastically decreased demand) may be more feasible, even with the lower penetration of renewables than in nations such as New Zealand.
	Climate, Agricultural resources and other factors	● Ireland has a humid, temperate climate (moderated by the North Atlantic Current), plentiful precipitation [83] and fertile soils in the eastern part of the island. ● It has a moderate per capita availability of agricultural land; this is, however, largely an artefact of the limited geographical area of the nation, given that the population is low, and the proportion of agricultural land is high. ● Agriculture in Ireland is extensive [97], varied in terms of produce and outputs, has high productivity and is a net exporter. ● In addition to extensive agricultural capacity, Ireland is not prone to major natural hazards, though extreme weather events have the potential to damage agricultural output, particularly considering the small land area of the nation.
	Overview	● Ireland has extensive renewable energy resources (primarily wind) which are currently only partially exploited and so have capacity for usage to increase in future, noting that fossil fuel generation currently dominates. ○ As such, any transition during a 'de-complexification' event would potentially be complicated relative to nations with current high existing renewables penetration but would still be favourable compared to the UK (with its more complex energy mix and high overall energy demand). ● Agricultural resources are extensive and generally favoured by climatic conditions (now and in the future) but have the potential to be impacted by extreme weather events. The small population of Ireland would likely offset limitations linked to its small geographical area and current reliance on fossil fuels, giving it the potential to comprise a future 'node of persisting complexity'.

4.2. Sustainability and Resilience Lessons

This analysis of 'nodes of persisting complexity' would be of limited value if it were simply a dispassionate analysis of what parts of human civilisation might survive a major, global scale 'de-complexification' in relatively unscathed forms. Such an event would be bleak, tragic and history-altering when the loss of life, knowledge and cultural achievements, which would inevitably be attendant to such scenarios, are considered. As such, this analysis is carried out with the intent to aid the understanding of what contributes to making such events possible or probable and, therefore, to act as a component of the feedback, which may reduce the risk of them occurring.

The analysis undertaken in Section 3 highlights that certain nations have particular characteristics ('favourable starting conditions') that may maximise their potential to form 'nodes of persisting complexity'. These characteristics are inherent to these locations, but there may be scope to apply aspects of these characteristics (or the benefits they naturally confer) to other locations that do not naturally have them. The application of learning from the 'nodes of persisting complexity analysis' may be possible through actions local to nations or global regions, and/or through global-scale actions. Some of these may be already underway, or may be things that are not yet happening, but which may be feasible in the future. The following subsections discuss the 'favourable starting conditions' in turn with reference to how they may be applied.

4.2.1. Future Climatic Conditions

Anthropogenically caused climatic change has the potential over the coming century and beyond to exacerbate conditions in regions already experiencing climate stresses and, in time, to significantly reduce the habitability of whole regions (e.g., by jeopardising reliable rain-fed agriculture) [75]. The changes will be subject to complex local factors (i.e., geographical and cultural features), but there may be several degrees of freedom/generalised actions available that could potentially be undertaken to reduce vulnerability to these future climatic changes.

At the global–national level, the minimisation of risks to regions that do not currently have benign climatic condition and/or which are unlikely to have resilience to changes may be best achieved through the international efforts to limit and mitigate greenhouse gas emissions. Given the uncertainty surrounding the scope and effectiveness of these international emission-reduction schemes, efforts at the national–local scale may potentially be more effective. These may include the variation of agriculture to adapt to changing conditions (including diversion from industrial monocultures towards widespread application of techniques such as permaculture [62], measures to minimise the vulnerability of soils to erosion under increased storminess and civil engineering to adapt to changing precipitation patterns (e.g., construction of reservoirs)).

4.2.2. Carrying Capacity

Prior to the modern era human societies were predominantly reliant on local/regional environments for key resources (e.g., food and metal ores). Constraints on the availability of localised resources (i.e., carrying capacities) were one of the main motivations underlying the expansion of historical nations and empires [5]. Colonialism, industrialisation, and the globalisation of supply chains has since reduced/removed the need for many nations to be self-reliant. This trend has increased global resilience to localised resource constraints whilst global resources remain plentiful (i.e., overall surpluses can be exported as needed) but has also increased overall global vulnerability to 'de-complexification'.

Where nations have become reliant on global supply chains their ability to utilise local resources may be degraded and/or local populations may have expanded per capita resource use beyond the local carrying capacity. This may result in a high degree vulnerability to the reduction or cessation of externally supplied resources. There would therefore be significant benefit in nations assessing alignment or mismatch with their local carrying capacity (now and in the future, based on projected changes in population, including from any potential large-scale inward migrations).

This could allow for the planning and implementation of measures to decrease vulnerability. This could include increasing the development and use of local resources (e.g., agricultural land and water resources, even if not currently the most cost-effective solution), reduction/elimination of reliance on resources/products that cannot be produced internally (e.g., agriculture reliant on imported fertiliser) and measures to decrease per capita resource usage. Such efforts could have the dual effect of reducing global resource consumption in parallel to increasing the resilience of regions and nations to global-scale events such as 'de-complexification'.

4.2.3. Indigenous and Resilient Energy Supplies

Energy is one of the metrics comprising carrying capacity as described above but is so fundamental that it warrants separate consideration. This is because modern technological societies are wholly reliant on a continual supply of energy (in primary form and as electricity) to maintain the functions that underpin complexity (e.g., supply of water services, logistics networks). The fossil fuels that supply the majority of the world's primary and secondary energy at a global scale are very unevenly distributed and, as such, are globally traded/supplied commodities. Therefore, nations that are reliant on imported energy (due to supply or economic factors) could be made highly vulnerable in a 'de-complexification' event leading to a cessation of large-scale energy resource distribution [50].

Renewable energy resources are inherently more evenly distributed than fossil energy resources, and most nations will have access to some renewable resources. Therefore, the development of renewables infrastructure would provide resilience to much of the world to interruption of global energy flows. Even if the amount of energy that could be supplied via indigenous renewables infrastructure would be relatively low in comparison to that supplied by fossil fuels via global supply chains, some continued availability of energy may provide resilience (i.e., by allowing vital functions and therefore a degree of complexity to be sustained).

4.2.4. Dependence on Global Supply Chains

As described in the previous subsection, modern societies are wholly reliant on technological systems, and these are in turn as reliant on the availability of manufactured items (i.e., parts and components). The capitalist economic system that has become dominant globally has led to global manufacturing becoming largely consolidated into a limited number of nations with favourable economic conditions, with low-cost logistics providing global distribution [5]. This situation potentially makes a significant number of nations with limited and/or inflexible manufacturing capacity vulnerable, i.e., a 'de-complexification' event may decrease the local availability of manufactured items.

The development or modification of a manufacturing base that could reliably supply key components necessary to the continued operation of fundamental systems (e.g., power networks, water supply infrastructure) may provide some degree of resilience against a reduction in the global availability of such items. Even if the local manufacturing capacity were limited and able to only produce relatively crude/simple items, this may provide resilience (i.e., by allowing vital functions and therefore complexity to be sustained to a degree).

4.2.5. Over-Reliance on High Levels of Complexity

Modern globalised society is characterised by high and continually growing levels of complexity (sociopolitical and technological). This has resulted from deliberate deployment of complexity to solve problems (i.e., increasing crop yields to feed growing populations) and as a self-reinforcing emergent property of complexity itself (e.g., development of computing technology leading to the internet). The deployment of complexity as a problem-solving strategy has become vital to the fundamental functioning of modern societies (e.g., provision of reliable food supplies), but it leads to a vulnerability in that societies become reliant on its continual smooth functioning and growth. This vulnerability grows as complexity increases and more and more societal functions become reliant on underpinning complexity [50].

Although it is likely to be difficult (practically and politically) to deliberately slow this trend and/or revert to less-complex structures, efforts to seek solutions to fundamental problems that are inherently simpler may provide many nations with an enhanced resilience against the failure of complexity and other major risks. Examples of such efforts would include building local renewable energy systems in favour of gas-fired generation capacity requiring global supply chains or a reduction in water demand in favour of building large-scale desalinisation infrastructure (such as that achieved in Cape Town in 2017–18 [98]).

4.3. Long Term Perspective

Given the human predicament and the challenges of seeking an effective means to navigate a safe path through it, a 'long-view' of humanity's situation that considers civilisation in a cosmic perspective may be useful. Modelling the complex feedback loops inherent to the interaction between theoretical 'exo-civilisations' (resource-harvesting technological civilisations equivalent to global human civilisation) provides a generalised context for the Anthropocene [99] which indicates that any civilisation intensively exploiting the resources of a closed planetary system will inevitably generate severe perturbation (i.e., through excessive entropy export to the surrounding environment) of its host system. The emergence of resource-depleting, self-destructive systems akin to the 'superorganism' [1] may be a thermodynamic inevitability [4] where intelligence evolves in a planetary environment with an excess of resources (and therefore may be a potential solution to the Fermi Paradox, i.e., a 'great filter').

A slight variation of this scenario [18] that may also place the trends of civilisation in perspective suggests that evolution may produce species with instincts and intelligence sufficient to build the tools to access and exploit the accumulated energy sources of a planetary environment but may be less likely to produce species able to build these capabilities and also to foresee the long-term consequences of the rapid depletion of a large resource endowment [52]. Given this perspective, the situation in which humanity finds itself currently may not be unique or unusual and may even represent something of an inevitability. If this is the case, the biggest challenge facing humanity may not be how to curtail the period of rapid growth after evolving the means to exploit a resource-rich environment (which evolutionary processes will equip intelligent species with tendencies to do). It may instead be long-term survival after the 'bottleneck' of collapse that becomes a high-probability event in such circumstances. The 'nodes of persisting complexity' that are the subject of this study could potentially be one of the factors in such long-term survival.

5. Conclusions

Human civilisation underwent increases in sociopolitical complexity since the Agricultural Revolution (ca. 100 centuries ago), the Industrial Revolution (ca. two centuries ago) and with exponential characteristics as part of the 'Great Acceleration' [2] (starting ca. 70 years ago). This generally has been characterised by phenomena such as large increases in population, energy use and interconnectedness and has resulted in increasingly extensive and severe perturbation of the Earth System and the biosphere. This perturbation has resulted in a wide range of effects and feedbacks on global human civilisation including (but not limited to) climate change, increased risk of pandemics, ecological destruction (manifesting as a sixth extinction event) and growing risks of systemic instabilities. In combination, these effects place complex human civilisation in a precarious and perilous position with regards to its future; the risk of an uncontrolled 'de-complexification' event (a systemic reduction in the overall complexity of civilisation at global scale) occurring may be increasing.

'De-complexification' has previously been described in the scientific and popular literature as 'collapse' (or alternative descriptors including 'the Olduvai Collapse' and 'the Great Simplification', which may take place through various rapid or prolonged mechanisms). The concept of 'lifeboats' has also been previously presented as a phenomenon that may emerge from 'de-complexification' events and generally describe geographical locations that have capacity (by virtue of natural features and/or potential for human action) to avoid the most egregious effects of climate change or other global events and therefore maintain significant populations. This study introduces an alternative description and narrative in the form of the 'node of persisting complexity'. These are defined as nations that may have certain characteristics ('favourable starting conditions') that may feasibly allow them to retain localised, higher levels of societal, technological and organisation complexity. A key difference with preceding narratives is that 'nodes of persisting complexity' would form through evolutionary system behaviour, rather than through any direct human agency.

The methodology for assessing which nations have the potential to form 'nodes of persisting complexity' utilises the outputs of the 'University of Notre Dame—Global Adaptation Index' (ND-GAIN) study, which assessed and ranked all nations in terms of vulnerability and readiness to future environmental change. The ND-GAIN ranking was screened against additional semi-quantitative measures specifically related to the 'nodes of persisting complexity' concept to generate a 'shortlist' of five nations (New Zealand, Iceland, the United Kingdom, Australia (Tasmania) and Ireland). Each of these was then further qualitatively assessed for their individual, local-scale (primarily energy and agricultural) characteristics. This identified New Zealand as having the greatest potential to form a 'node of persisting complexity', with Iceland, Australia (Tasmania) and Ireland also having favourable characteristics. The United Kingdom presents a more complex picture and potentially has less favourable characteristics overall.

The analysis of the possible systemic evolution of global complexity is by itself of limited potential value, so this study applies the analysis of the 'nodes of persisting complexity' to identify potentially useful insights for enhancing resilience for nations that do not have the natural confluence of 'favourable starting conditions'. This analysis identifies that actions that may provide the means to address the interlinked factors of climate change, carrying capacity, indigenous energy and manufacturing capacity and the over-reliance on complexity might provide the greatest resilience against future 'de-complexification'. Overall, the human predicament of exceeding global environmental limits, creating unmanageable and increasingly ineffective complexity and perturbing global life support systems may be typical of any energy and material resource-harvesting civilisation in a constrained environment. In this context, 'nodes of persisting complexity' may provide the greatest opportunity for human society to retain technology and organisation into the longer term.

Author Contributions: Conceptualization, N.K. and A.J.; methodology, N.K.; formal analysis, N.K.; writing—original draft preparation, N.K.; writing—review and editing, A.J.; supervision, A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data included in the paper.

Acknowledgments: The authors would like to thank the constructive comments and engagement with the paper from our four reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. ND-GAIN Ranking of Highest-Scoring Nations

Table A1. Ranking of ND-GAIN Highest-Scoring Nations.

Rank	Country
1	Norway
2	New Zealand
3	Finland
4	Denmark
5	Sweden
6	Switzerland
7	Singapore
8	Austria
9	Iceland
10	Germany
11	United Kingdom
12	Luxembourg
13	Australia
14	Korea
15	Japan
16	The Netherlands
17	France
18	Canada
19	United States
20	Ireland

Appendix B. ND-GAIN Vulnerability Indicators

Table A2. ND-GAIN Vulnerability Indicators.

Sector	Exposure Component	Sensitivity Component	Adaptive Capacity Component
Food	Project change of cereal yields	Food import dependency	Agriculture capacity (fertiliser, irrigation, pesticide, tractor use)
	Projected population change	Rural population	Child malnutrition
Water	Projected change of annual runoff	Freshwater withdrawal rate	Access to reliable drinking water
	Projected change of annual groundwater recharge	Water dependency ratio	Dam capacity
Health	Projected change of deaths from climate change induced diseases	Slum population	Medical staffs (physicians, nurses and midwives)
	Projected change of length of transmission season of vector-borne diseases	Dependence on external resource for health services	Access to improved sanitation facilities
Ecosystem services	Projected change of biome distribution	Dependency on natural capital	Protected biomes
	Projected change of marine biodiversity	Ecological footprint	Engagement in international environmental conventions
Human habitat	Projected change of warm period	Urban concentration	Quality of trade and transport-related infrastructure
	Projected change of flood hazard	Age dependency ratio	Paved roads
Infrastructure	Projected change of hydropower generation capacity	Dependency on imported energy	Electricity access
	Projection of Sea Level Rise impacts	Population living under 5 m above sea level	Disaster preparedness

Appendix C. ND-GAIN Readiness Indicators

Table A3. ND-GAIN Readiness Indicators.

Component	Indicators			
Economics readiness	Doing business			
Governance readiness	Political stability and non-violence	Control of corruption	Rule of law	Regulatory quality
Social readiness	Social inequality	ICT Infrastructure	Education	Innovation

Appendix D. Calculation of Agricultural Land per Capita

Table A4. Calculation of Agricultural Land per Capita.

Country	Carrying Capacity Analysis (Approximate, Rounded Agricultural Land/Capita)
Norway	5.5 million total population [71] 365,268 km^2 total land area [100] 0.27% agricultural land [72] **0.002 km^2 agricultural land/capita**
New Zealand	5.0 million total population [71] 263,310 km^2 total land area [100] 43.2% agricultural land [72] **0.023 km^2 agricultural land/capita**
Finland	5.6 million total population [71] 303,890 km^2 total land area [100] 7.5% agricultural land [72] **0.004 km^2 agricultural land/capita**
Denmark	5.9 million total population [71] 42,430 km^2 total land area [100] 63.4% agricultural land [72] **0.005 km^2 agricultural land/capita**
Sweden	10.3 million total population [71] 410,340 km^2 total land area [100] 7.5% agricultural land [72] **0.003 km^2 agricultural land/capita**
Switzerland	8.5 million total population [71] 39,516 km^2 total land area [100] 38.7% agricultural land [72] **0.002 km^2 agricultural land/capita**
Singapore	5.9 million total population [71] 700 km^2 total land area [100] 1% agricultural land [72] **Negligible agricultural land/capita**
Austria	8.9 million total population [71] 82,409 km^2 total land area [100] 38.4% agricultural land [72] **0.004 km^2 agricultural land/capita**
Iceland	354,000 total population [71] 100,250 km^2 total land area [100] 18.7% agricultural land [72] **0.053 km^2 agricultural land/capita**
Germany	79.9 million total population [71] 348,560 km^2 total land area [100] 48% agricultural land [72] **0.002 km^2 agricultural land/capita**

Table A4. *Cont.*

Country	Carrying Capacity Analysis (Approximate, Rounded Agricultural Land/Capita)
United Kingdom	66.1 million total population [71] 241,930 km^2 total land area [100] 71% agricultural land [72] **0.003 km^2 agricultural land/capita**
Luxembourg	640,000 total population [71] 2590 km^2 total land area [100] 51% agricultural land [72] **0.002 km^2 agricultural land/capita**
Australia	25.8 million total population [71] 7,682,300 km^2 total land area [100] 52.9% agricultural land [72] **0.158 km^2 agricultural land/capita**
Korea	51.7 million total population [71] 97,230 km^2 total land area [100] 18.1% agricultural land [72] **Negligible agricultural land/capita**
Japan	124.7 million total population [71] 364,555 km^2 total land area [100] 12.5% agricultural land [72] **Negligible agricultural land/capita**
The Netherlands	17.3 million total population [71] 33,720 km^2 total land area [100] 55.1% agricultural land [72] **0.001 km^2 agricultural land/capita**
France	68.1 million total population [71] 547,557 km^2 total land area [100] 52.7% agricultural land [72] **0.004 km^2 agricultural land/capita**
Canada	37.9 million total population [71] 9,093,510 km^2 total land area [100] 6.8% agricultural land [72] **0.016 km^2 agricultural land/capita**
United States	335 million total population [71] 9,147,420 km^2 total land area [100] 44.5% agricultural land [72] **0.012 km^2 agricultural land/capita**
Ireland	5.2 million total population [71] 68,890 km^2 total land area [100] 66.1% agricultural land [72] **0.009 km^2 agricultural land/capita**

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