

Energy constrains to increasing complexity in the biosphere

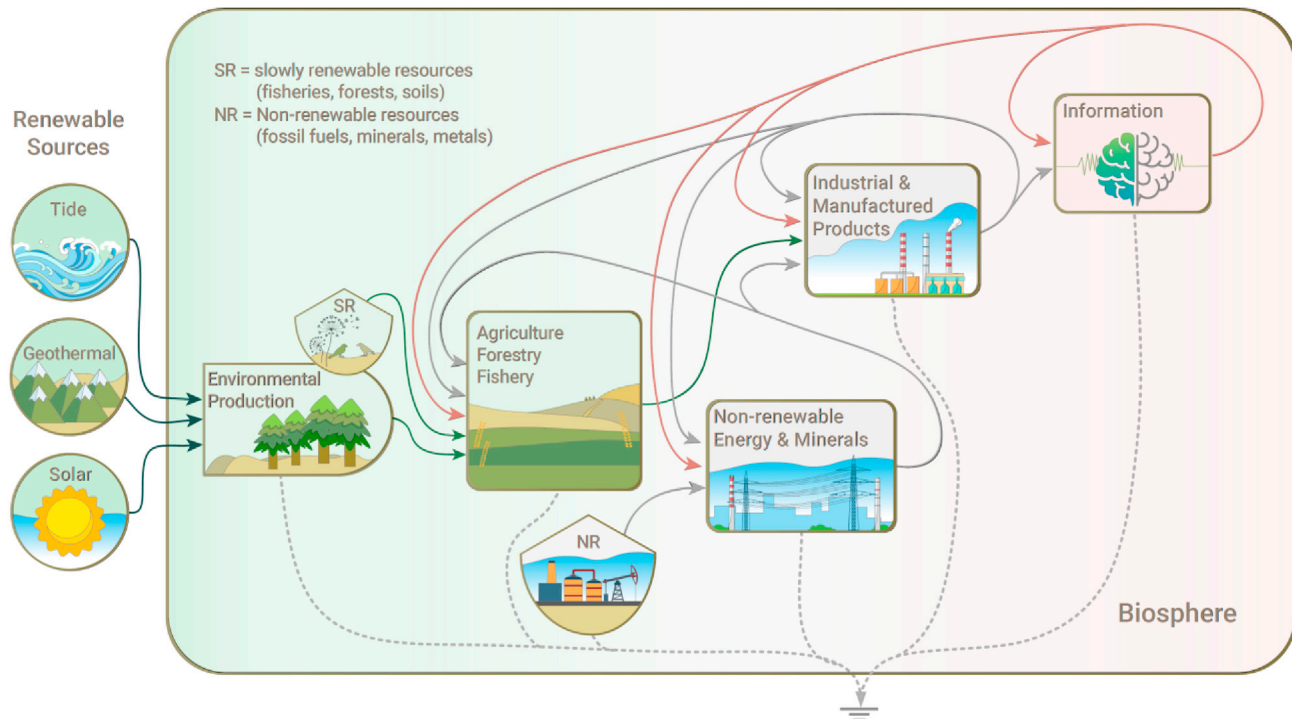
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Graphical abstract



Public summary

- A well-defined representation of the self-organizing hierarchical structure of biosphere is provided
- Additional evidence shows transformation processes result in work potentials (exergy) of differing quality depending on placement within the hierarchy
- Expansion of higher levels of organization (i.e., information) are constrained by availability of resources requiring investments of nearly 20,000 times the energy invested at the top of the biosphere hierarchy
- The understanding of energy constrains may lead to better resource management and economic policy perspectives



Energy constrains to increasing complexity in the biosphere

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Thirty years ago, the systems ecologist Howard T. Odum introduced the concept of transformity, which is a thermodynamic measure of quality within the trial and error evolutionary dynamics of ecosystems, namely an indicator of rank in the hierarchical system structure of the biosphere. Based on a global database of individual processes and whole economies, this paper extends, refines, and updates Odum's idea, demonstrating the strength of the postulated relation. In particular, an inverse linear logarithmic relationship is shown to hold between resource quantity (exergy) and quality (emergy), which is the result of an overall energetic efficiency characteristic of energy transformation processes of the biosphere. This relation extends from natural renewable energy sources to human information (including global internet data flows) and know-how embedded in national economies, thus identifying a consistent theory of hierarchical organization of the biosphere grounded in energetics and ultimately setting constraints to illusions of unlimited growth.

Keywords: complexity; self-organizing system; hierarchical structure; energetic efficiency

INTRODUCTION

The concept of self-organization, i.e., the spontaneous emergence of ordered structures from interactions among initially disordered parts, permeates all branches of science, including natural and, among others, physical sciences,^{1,2} social theories, informatics, and economics.^{3–7} As an organizing principle of complex systems, it has allowed science to overcome the limitations of the deterministic approach to natural laws and a thermodynamic paradigm that forbids increases in order in a world of increasing entropy.

Thirty years ago, the article "Self-organization, transformity and information" by H.T. Odum, based on his acceptance lecture for the Crafoord Prize of the Royal Swedish Academy of Sciences, was published in *Science*.⁸ It extended the purely ecological meaning of self-organization, suggesting the existence of an energy hierarchy within biosphere transformation processes, including human systems and information. A main facet of the energy hierarchy concept was the concept of *energy quality*, expressed by the amount of one form of available energy (i.e., exergy) required to generate an output form. This ratio was called *transformity*, applicable to materials, energy sources, and information processes. The total available energy, directly or indirectly required over the whole supply chain to generate an output product or service, is named *emergy*. *Solar emergy*, whose units are *solar emjoules* (sej), is the form of emergy commonly used to express the different flows of energy and resources within a system on the same solar-referred

basis. In his 1988 *Science* article, H.T. Odum, postulated that transformity "... may be used as an energy-scaling factor for the hierarchies of the universe including information."

Because of the thermodynamics of all transformation processes, more available energy is consumed than provided (as is well known, the coal to electricity conversion requires roughly 4 joules of coal to make 1 joule of electricity), but the output that is delivered is of a higher quality, leading to another assertion by Odum "... a transformation is useful only if it is to a higher quality, that can amplify more with less energy."⁹ It is a hypothesis that self-organizing systems use stores and flows of energy, materials, and information for purposes commensurate with what is required for their formation. Therefore, a joule of electricity should be capable of doing at least the work of 4 joules of coal.¹⁰ The immediate consequence is that higher-quality processes (electricity, information flows, and networks, such as the internet) have huge costs, supported by a much larger base of diverse and lower-quality resources, placing an upper limit to the growth of natural and human-dominated assets.¹¹

The concepts of emergy and transformity contributed to an integrated description of the biosphere as a system of transformation processes yielding ever more complex and higher-quality components. While not exempt from initial criticisms,¹² this theory, now widely cited, led to its application at multiple scales, from DNA to biological systems,^{13,14} to galaxies¹⁵ (e.g., some researches extended the embodied solar energy to embodied cosmic exergy based on the revealed scarcity of cosmic exergy availability in the material earth¹⁶), and including both natural and anthropic processes. Since the publication of Odum's seminal paper,⁸ many applications of emergy, evaluating products and processes, have led to resource management suggestions and policy alternatives. The number of research articles that have employed emergy, as cited in two recent papers,^{17,18} has totaled over 700 by 2014, with several papers recently stressing the relationship between emergy and exergy.^{19–22} While there have been a wealth of papers that use emergy for case studies and methodological improvements, especially at technological,²³ industrial,²⁴ regional,²⁵ national,²⁶ and global levels,²⁷ only a recent one²⁸ has started exploring the implications of Odum's original propositions⁸ using empirical data from the literature. However, while Odum's paper explored the hierarchical organization using the transformity concept (by collecting over 700 transformities from the literature), there are still issues with the method employed, that need to be addressed and refined. In fact, the study plotted energy against transformity, implicitly assuming that all previous quantifications were based on available energy (exergy). Moreover, it included both material and energy flows, mixing mass and energy values. By contributing to a rough first exploration of the relation between energy quality and quantity, a study²⁸ provided the opportunity for further refining and deeper understanding. Using exergy, as we do in this study, it removes

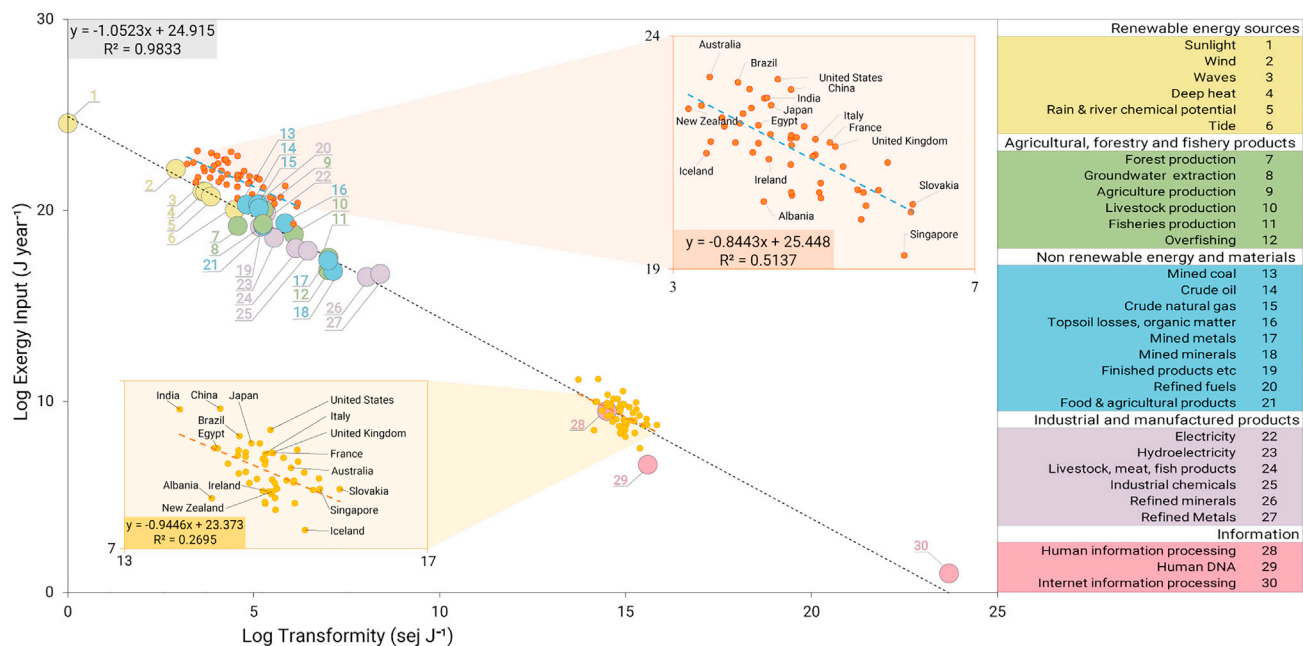


Figure 1. Log-log plot of transformity versus available energy for hierarchical transformation processes of the biosphere The large dots, represent five different groups (and colors) of aggregate transformation processes and their respective products: renewable energy sources (1–6), agricultural, forestry, and fishery products (7–12), non-renewable energy and materials (13–21), industrial and manufactured products (22–27), and information (28–30). Small orange dots depict the average performance (sej J⁻¹) of 37 “developed” and 13 “developing” economies. The small yellow dots show transformity of information of each country’s population plotted against the exergy of the information representing human know-how.

some ambiguities and apparent contradictions of using different types of energy and allow an appropriate comparison of systems belonging to different categories. In addition to using exergy, our study adopts a different grouping scheme of processes to escape the risk that a *priori* choices affect the final results.

In this study, we provide a well-defined representation of the self-organizing hierarchical structure of the biosphere and additional evidence that transformation processes result in work potentials (exergy) of differing quality, depending on their placement within the hierarchy, providing new insights for understanding the complex systems of which humans are a part. Such an understanding may lead to better resource management and economic policy perspectives. For instance, while there has been much talk of human society entering an information age, where information becomes the driving force of all economic productivity, such an age is highly unlikely if there is not sufficient available energy to power the underpinning hierarchy of processes that make information generation possible. Through this study, we document an overall macro transfer efficiency of the biosphere and suggest that expansion of higher levels of organization (i.e., information) are constrained by availability of resources requiring investments of nearly 20,000 times the energy invested at the top of the biosphere hierarchy.

RESULTS

Figure 1 shows a set of processes and national economies, whose performances are graphed as exergy of input (theoretical work potential of resources) on the vertical axis versus quality of output (transformity = total driving energy/exergy of process output) on the horizontal axis (calculations are shown in the supplemental information). When the biosphere is viewed as a self-organizing hierarchical system of energy transformations, items at higher hierarchical level are characterized by smaller output exergy, while the quality of the output increases in a logarithmically linear fashion.

The large dots represent four different groups (and colors) of aggregate transformation processes and their respective products: renewable energy sources (1–6), agricultural, forestry, and fishery products (7–12), non-renewable energy and materials (13–21), and industrial and manufactured products (22–27). When graphed as in Figure 1 on a log-log plot, a linear regression (black dotted line; R² = 0.98; r = -1.05) is obtained, showing an

average stable relation between energy quantity and quality. The relation suggests that an increase of energy quality (i.e., transformity) by one order of magnitude may correspond to only 14% of the input exergy transferred to the higher quality level, while the remaining 86% is dispersed; in other words, it results a relative efficiency of 14%.

Figure 1 also shows a cluster of smaller orange dots, denoting input exergy and energy intensities for 37 developed and 13 developing economies (energy intensity = total driving energy/exergy of country output) (see supplemental information; Table S3). The dots depict the average performance (sej J⁻¹) of these countries plotted against the exergy of their inflowing resources. The available data show a log-linear scaling for countries’ energy intensities, which are located in the region between 3 and 7 of log transformity (Figure 1, orange small dots; R² = 0.79; r = -0.94). The regression line of countries lays slightly above the regression line of the aggregate transformation processes (large dots) displaying higher exergy use for the same average energy intensity, indicative of a lower overall efficiency of transformation of resources into national economic output.

The cybernetic nature of ecosystems, as well as socio-economic systems,²⁹ is another perspective that was discussed in Odum’s paper in *Science* 30 years ago. Like natural ecosystems, socio-economic systems develop, use, and feedback information in actions that coordinate, regulate, and control the transformation of matter and energy.³⁰ Both Odum⁸ and Abel³¹ have pointed out that the creation of information occurs in transformation processes, driven by essential energy inputs. Information, complexity (i.e., the presence of structured systems), and energy inputs are inextricably related.³² In Figure 1, three transformities of information (red dots) are included, showing a continuation of the trend line found for the aggregate process data. The three transformities are, human information processing (log transformity = 14.5), human DNA (log transformity = 15.6), and world wide web information processing (log transformity = 23.7).

In addition to the large red dots representing three different scales of information processing, the cluster of small yellow dots represents the transformity of human information for 37 developed and 13 developing economies (see supplemental information; Table S8). The data represent the transformity of information of each country population plotted against the exergy of the information and are suggestive of human know-how of each economy.³³ It is

neither the information content of the biodiversity nor the information content of human DNA but, instead, the information content, in the form of know-how of socio-economic systems.

DISCUSSION

Tradeoff between complexity and scale

Transfer efficiencies have been used to infer the amount of production at higher hierarchical levels that production at lower levels can globally support.³⁴ The quantification of transfer efficiencies help to understand the link of individual processes to larger-scale processes within systems.³⁵ This fraction of transferred exergy is well within the range of transfer efficiencies postulated by Lindeman³⁶ and Pauly and Christensen.³⁷ An average 14% transfer efficiency is much lower than the 50% efficiency postulated by Odum and Pinkerton³⁸ as the optimum for maximum power output by physical and biological systems. Their optimum efficiency, of course, is hardly if ever achieved, but the fact that the myriad transformation processes of the biosphere find an overall efficiency of 14% supports the conjectures of Lotka³⁹ and Odum^{8,9} that "... one of the many realities of the natural world is that living and also man-made processes do not operate at the highest efficiencies that might be expected of them," but instead, sacrifice efficiency for more power output.

In 1906, Pareto defined human society as a hierarchical collectivity, and postulated what was termed Pareto's law on the distribution of income.⁴⁰ He derived the well-known log-log relationship between the number of individuals receiving an income at or above a certain amount plotted against the total income of the selected population (i.e., a cumulative distribution). The straight line observed by Pareto allowed him to postulate that, due to the rigidity of the distribution, there was only one way to increase economic welfare (i.e., the share of the poorer classes in the national income), and that was to increase total production of the economy. Zipf, based on his original rank size distribution of cities⁴¹ found much the same relationship as Pareto when he graphed empirical data of such things as: number of businesses versus number of businesses of like kind, number of employees versus number of specific occupations, and the size of cities versus their rank. Zipf's number-frequency relationships have the same form as do those of Pareto, expressed by a linear equation relating the log of the number of individuals in any class X , and the log of X . Both Pareto and Zipf suggested that these relationships indicate a measure of organization and that departures from straight line slopes indicate disunity⁴⁰ or inequality.⁴¹

Here, we postulate the existence of a simple rule to explain the apparent Pareto and Zipf distribution of phenomena. The available energy output of any transformation process (product, service, earthquake, war, economic system, etc.) requires, on average, at least 7 times the available energy as input. This is not to say that all transformation processes strictly adhere to this $7\times$ rule, only that, across the 24 orders of magnitude of energy intensity found in the biosphere, the average transfer efficiency is 14%, thus yielding the 7:1 ratio of input to output.

While rank size distributions describe the existence of a constant relation between the size of cities, for instance, these ranks, based on observations, do not provide an explanation on the cause of this phenomenon. Here, we suggest a mechanism. The concentration of enough available energy to support a higher-level component within a landscape requires many processes, each yielding a small but significant quantity of available energy, that, when added together with others of the same size, results in a sufficient quantity of available energy to support the higher-level component. This is quite evident in ecological food chains, where many smaller organisms are thermodynamically necessary to support larger organisms at higher trophic levels, the end result of which is a hierarchy of energy transformations. As a consequence of the second law of thermodynamics, biosphere transformation hierarchies cannot be flat, just as it is impossible to have flat food pyramids in ecology.

Bear in mind that while the "currency" of ecosystem food chains is carbon, and they represent relatively simple hierarchical organization, the self-organizing hierarchy of the biosphere we describe here is composed of many different hierarchies of different kinds (i.e., ecological, technological, social, and economic). While each has its characteristic structural organization,

they fit within the larger biosphere by virtue of their overall available energy flow and transformity. We suggest that there is a natural hierarchy of energy transformation processes of the biosphere and that the transformity of any single process provides information on its place within the hierarchy.

In general, our data suggest that there is continuity to the hierarchical system of the biosphere organized as a power law (power law exponent = -1.054), which indicates a high degree of self-organization. Odum had postulated that self-organization results from the maximization of power,⁹ a characteristic of natural and human-dominated systems. Bejan and Lorente⁴² have suggested that self-organization results in configurations (arrangements, patterns) that provide greater and greater access to the available energy that flow through them. These scaling relationships ultimately help explain and predict transformation processes emerging at all levels of hierarchical organization at different scales in time and space.

The regression lines in Figure 1 provide an interesting relation and a general theorem that relates the work potential of resources (exergy) to a system performance through its energy intensity. The sum of the independent exergy inputs that drive the biosphere (solar, tidal, and geothermal exergy) yields a log of about 24, while the corresponding log transformity is zero. On the other hand, when the log of exergy tends toward zero the log transformity tends to a maximum value of 24; a boundary that may represent the highest achievable process of ordering and energy concentration in the biosphere.

Odum's self-organization theory⁸ provides a fascinating array of quantitative predictions about natural and human-dominated systems. The results of our analysis of these global data is consistent with Odum's postulated scaling relationship and suggests three interesting suppositions: (1) the amount of exergy lost (dissipated) in the cascade of transformation steps in the energetic systems of the biosphere is consistently about 86%; (2) the existence of a higher boundary of energy quality in the biosphere expressed as log transformity about 24 (Figure 1); and (3) a general theory of scaling in energy transformations of self-organizing systems that leads to hierarchical organization.

Multi-scale evolutionary processes

Although the discussions above help us recognize the fundamental properties and limitations of systems, our understanding of most complex systems will inevitably be imperfect and incomplete; and, regardless of how well considered a plan is, a truly complex system will always present elements that were not considered ahead of time. Natural and human-dominated systems of the biosphere are constrained by the availability of renewable and non-renewable exergy and at the same time affected by relatively low-efficiency conversion rates, yet they self-organize into complex hierarchical structures to optimize benefits. This complexity is made possible by transformation processes that degrade considerable quantities of available energy, and then generate smaller amounts of higher-quality energy and material flows, which are capable of greater useful work and feedback control on lower hierarchical levels, thus finally improving sustainability, furthering complexity and increasing dynamic stability. Given the absence of perfect knowledge, how can the success of systems we design or are part of be assured? While the success of many systems rests on the assumption that good decisions will be made, some systems may perform very well despite the fallibility of the decision makers. The study approaches this observation scientifically by (implicitly or explicitly) considering the decision makers themselves as part of the system and of limited complexity/decision-making ability. The question, thus, becomes: how do we design systems that exceed the complexity of the decision makers within them?

The common characteristic of these systems is their embodiment of some sort of evolutionary process, i.e., a process in which successful changes are followed and further modified by other systems while unsuccessful changes are not. The classical evolutionary processes are the biological ones. Due to variability introduced by random mutations, organisms with the complexity and scale of humans evolved from single-cell organisms. Exposure to random shocks affect socio-economic systems dynamics (see Figure 2 and Table S9 in supplemental information). Most countries have a higher transformity, moving from left to right from 2001 to 2014,

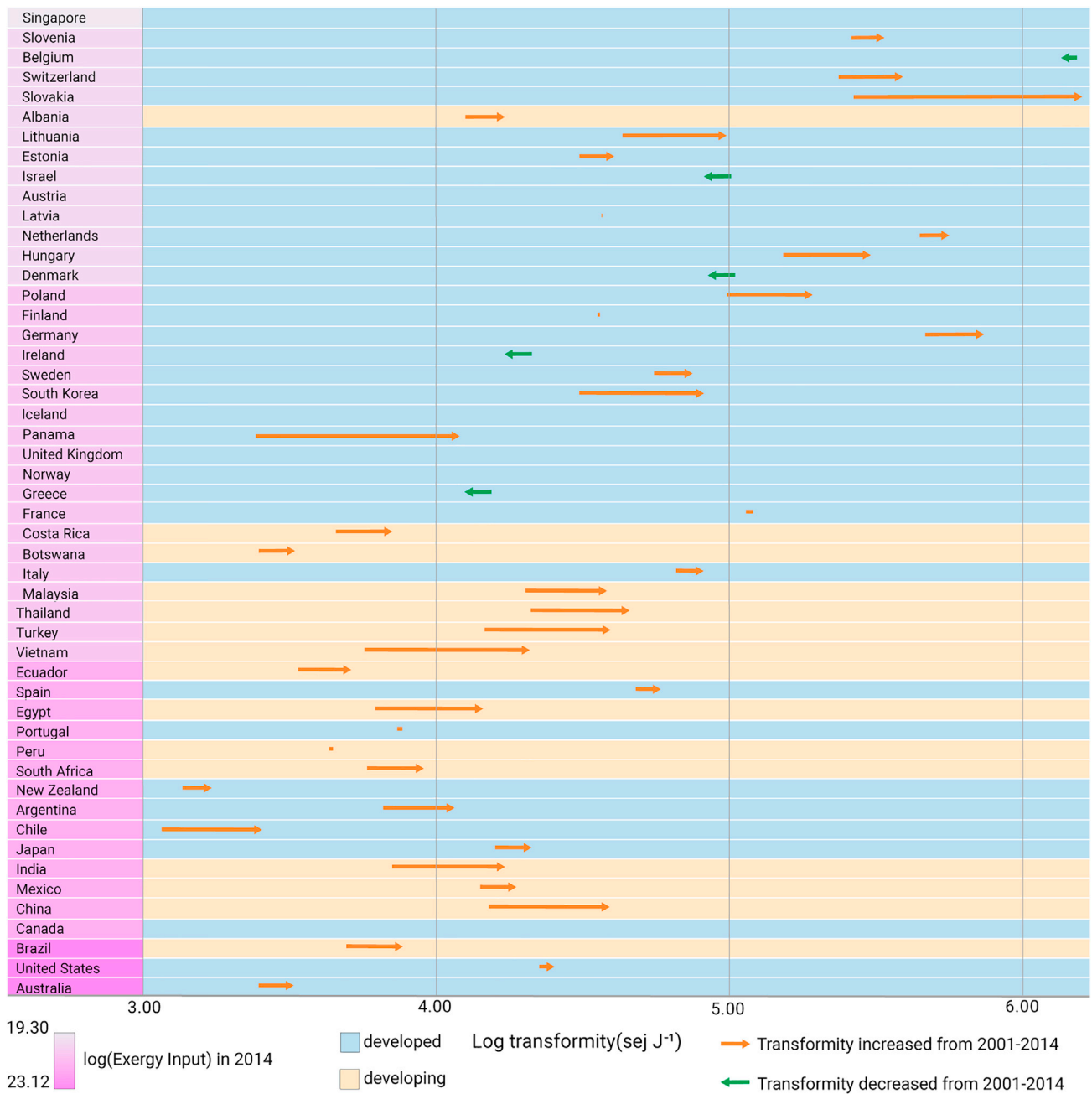


Figure 2. The development changes from 2001 to 2014 in 50 countries The developed countries are highlighted in blue and the developing countries are in yellow.

and a few countries have lower transformities, moving from right to left, with no change for Canada and the United Kingdom. Developed countries are generally on the top of the figure, indicating that the quality (resource use, production processes, etc.) of developed countries is higher, while developing countries are generally placed on the bottom.

The practical applications of these relations highlight the importance of a consistent theory of hierarchical organization grounded in energetics. While some relate the number of processes in a system only with size, surely being a relevant factor, the underlying flows of available energy (true drivers of complexity) remain hidden when plotting size versus complexity, as they are two sides of the same coin. As shown in this study, complexity results from hierarchical self-organization, being, in turn, the natural outcome of systems of energy transformations.

It is important to distinguish between the complexity of a hierarchy and the complexity of decision making of a certain community, national government,

or larger-size organization. No type of hierarchy is inherently better than any other. For a particular resource endowment and emergy-driven pattern, the best hierarchy is the one whose complexity profile matches the tasks that it is trying to perform. Consequently, policy makers should consider not just the overall complexity profile of countries but also how well subdivisions in countries match those within their resource endowment and emergy-driven pattern.

The relations highlighted in this paper provide an unambiguous assertion that transformation hierarchies affect the allocation of resources. Thus, the growth of higher-quality components (technology, information, government, etc.) requires not only the necessary resource investment to drive the component, but all the exergy necessary for the lower levels of the hierarchy that support it. If we assume a five-component hierarchy, the addition of one unit of exergy at the top hierarchy level, on average requires investment of about 19,000 units at the bottom ($1/(14\% \times 14\% \times 14\% \times 14\% \times 14\%)$).

To put it another way, transformities are a way of indicating that, for each unit of exergy of a given resource quality, it takes investment of much larger quantities in lower levels of the hierarchy. As a consequence, continued expansion of high-quality components, such as information, is not merely an investment of direct exergy in education, but investment in the entire exergy “food web” that is necessary to support it. Transformity is a way of acknowledging the quantity of the required indirect investments.

Practically speaking, as the world strives for organization of higher levels of complexity (larger corporations or global governmental entities, etc.), these higher hierarchical levels require enormous quantities of resources for their direct and indirect support. However, as the total quantity of energy is limited, the size and complexity of global hierarchies is limited. This might lead to instabilities and eventual collapse of complex organizations or societies. This depends on the fact that increasing complexity (i.e., the addition of structures, specializations, and connections among them) necessitates a greater energy availability, generating a pressure on resources, under which past societies have collapsed.⁴³ Results, then, suggest that future research should be directed toward the analysis of available energy hierarchies in larger-scale organizations, such as the United Nations, the European Union, NATO, international trade agreements, and major global banks.

MATERIALS AND METHODS

Data compilation

Recent analysis and data mining of large global datasets of energy, material, and information flows have allowed us to revisit the energetic basis for hierarchical self-organization first posited by H.T. Odum in *Science* in 1988.⁹ Using statistical data from 213 countries (derived from the National Energy Accounting Database [NEAD]) (NEAD: <http://www.emergy-nead.com/home>, see supplemental information), we have computed exergy content of aggregated classes of energy, materials, and information flows supporting the production processes of the global economy.

NEAD compiles detailed information for over 213 countries/regions for the full array of resources that underlie economies. These include environmental flows (e.g., solar radiation, tidal momentum, and geothermal exergy, as well the available energy in precipitation, wind, and waves), the flows of natural capital stocks (e.g., soil, water, forests, fish), mined materials (e.g., metals, fuels), and economically transformed goods and services (e.g., agricultural commodities, manufactured goods, services).

Using standard conversions (mass = J/kg, energy = high heat values) we computed exergy of individual material and energy flows supporting countries, then they were combined (summed) into the aggregate flows listed in Figure 1. NEAD contains a full list of energy intensities or unit exergy values (UEVs = sej J^{-1} or sej kg^{-1}) for commodity, mineral, and energy flows. A weighted average transformity was computed for each of the aggregate flows. The large dots represent the exergy of global flows of each aggregate flow versus the transformity of that flow.

The data for the two sets of smaller dots were handled in a similar way as the data for the global dataset. Emergy intensities (sej J^{-1}) of economies (small yellow dots) were computed by dividing the sum of emergy inputs by the sum of the exergy of the output of each country. The exergy and transformity of country know-how (small red dots) were computed by dividing the emergy input by the exergy of human information processing. Full details of these calculations can be found in the supplemental information.

Significance statement

In this study, we provide a well-defined representation of the self-organizing hierarchical structure of the biosphere and additional evidence that transformation processes result in work potentials (exergy) of differing quality depending on placement within the hierarchy, providing new insights for understanding the complex systems of which humans are a part. Such understanding may lead to better resource management and economic policy perspectives. For instance, while there has been much talk of human society entering an information age, where information becomes the driving force of all economic productivity, such an age is highly unlikely if there is not sufficient available energy to power the underpinning hierarchy of processes that make information generation possible. In this study we document an overall macro transfer efficiency of the biosphere and suggest that expansion of higher levels of organization (i.e., information) are constrained by availability of resources requiring investments of nearly 20,000 times the energy invested at the top of the biosphere hierarchy.

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AUTHOR CONTRIBUTIONS

G.L. and Z.Y. were responsible for overall project supervision, conceptualization, data curation, and project management. B.F.G., M.C., F.A., F.G., and C.M.V.B.A. provided early conceptualization of the project direction. G.L., J.P., N.Y., Y.H., and L.Z. were instrumental in formal analysis of data. G.L., M.C., M.T.B., and S.U. contributed to methodology development, conducted validation, and contributed to the writing of early drafts and final draft review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

LEAD CONTACT WEBSITE

Data are available at NEAD website: <http://www.emergy-nead.com/home>.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.xinn.2021.100169>.