DYNAMICS OF SOCIOECOLOGICAL SUSTAINABILITY BASED ON NATIONAL FOOTPRINT ACCOUNTS (1961-2014)

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by
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ABSTRACT

The project of international development has been extensively and profoundly questioned. A fixation on economic growth, narrowly represented by income *per capita* metrics (e.g.: gross domestic product – GDP), has been the focus of particularly astringent criticism. Nevertheless, taxonomies distinguishing developed, developing, and underdeveloped countries (or similar categories), based on income *per capita* metrics, are still prevalent analytical tools in the realm of international discussions about social progress and in lay discourse. To contribute to the creation of a 'dashboard' of indicators reflective of a multidimensional notion of social progress, I analyze 53 years of data of the two components of the National Footprint Accounts, Biocapacity and Ecological Footprint *per capita* for 123 nations between 1961 and 2014. Using a simplified description of the joint trajectories of these components, I perform cluster analysis. The patterns that emerge allow me to describe the dynamics of sustainability for the study period by formulating a taxonomy of socio-ecological change. This research contributes to expand and improve our understanding of social progress from the point of view of sustainability. My description of the dynamics of sustainability, contributes to re-framing social progress from a notion of unbounded accumulation of wealth to a notion of political, uneven contest concerning people and natural resources. This taxonomy offers an opening to engage with social issues like widening and narrowing differences among nations (convergence/divergence), environmental or ecological (in)efficiency, unequal exchange, unequal ecological exchange, and ecological debts.

BIOGRAPHICAL SKETCH

Manuel Berrio is a father, husband, son, brother, and friend. He graduated as a biologist from *Universidad Nacional de Colombia* (*Bogotá*). He also holds specialist degrees in Environmental Impact Assessment from *Universidad de Bogotá Jorge Tadeo Lozano* and Geographic Information Systems from *Instituto Geográfico Agustín Codazzi*.

"Throughout the 17th and 18th centuries, and for most of the 19th century, the exploitation of Africa and African labour continued to be a source for the accumulation of capital to be re-invested in Western Europe. The African contribution to European capitalist growth extended over such vital sectors as shipping, insurance, the formation of companies, capitalist agriculture, technology, and the manufacture of machinery. The effects were so wide-ranging that many are seldom brought to the notice of the reading public. For instance, the French St. Malo fishing industry was revived by the opening up of markets in the French slave plantations; while the Portuguese in Europe depended heavily on dyes like indigo, camwood, Brazilwood, and cochineal brought from Africa and the Americas. Gum from Africa also played a part in the textile industry, which is acknowledged as having been one of the most powerful engines for growth within the European economy. Then there was the export of ivory from Africa, enriching many merchants in London's Mincing Lane, and providing the raw material for industries in England, France, Germany, Switzerland, and North America — producing items ranging from knife handles to piano keys.…

In speaking of the European slave trade, mention must be made of the U.S.A., not only because its dominant population was European, but also because Europe transferred its capitalist institutions more completely to North America than to any other part of the globe, and established a powerful form of capitalism — after eliminating the indigenous inhabitants and exploiting the labour of millions of Africans: Like other parts of the New World, the American colonies of the British crown were used as means of accumulating primary capital for re-export to Europe. But the Northern colonies also had direct access to benefits from slavery in the American South and in the British and French West Indies. As in Europe, the profits made from slavery and slave trade went firstly to commercial ports and industrial areas, which meant mainly the north-eastern sea-board district known as New England and the state of New York. The Pan-Africanist, W. E. B. Du Bois, in a study of the American slave trade, quoted a report of 1862 as follows:

> 'the number of persons engaged in the slave trade and the amount of capital embarked in it exceed our powers of calculation. The city of New York has been until of late (1862) the principal port of the world for this infamous commerce; although the cities of Portland and Boston be only second to her in that distribution'."

Walter Rodney (1973) How Europe Underdeveloped Africa [1],
whom I found myself reading in June 2020.

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LIST OF ABBREVIATIONS

AU: Approximately unbiased probabilities

BC: Biocapacity (national)

BCP: Biocapacity *per capita*

EF: Ecological Footprint (national)

EFP: Ecological Footprint *per capita*

GDP: Gross Domestic Product

GFA: Global Footprint Network

gha: Global hectares

GNI: Gross National Income

GNP: Gross National Product

IPBES: International Panel on Biodiversity and Ecosystem Services

ISO: International Organization of Standardization

KPSS: Kwiatkowski–Phillips–Schmidt–Shin (stationarity test)

NFA: National Footprint Accounts

UNDP: United Nations Development Programme

ISO two-letter codes [2] are included in Appendix 5

PREFACE

> "Finding creative, effective, viable solutions to shape humans' way of life into a coherent system with nature is the most pressing and inspiring challenge of our time. It is my goal to participate in our joint building of understanding of the workings of societal change and the construction of a framework for socially, economically, and environmentally responsible decisions relative to human development projects"[1].

What is the problem?

Income metrics (Gross Domestic Product (GDP), Gross National Income GNI), and Gross National Product(GNP)), their *per capita* variants, orthodox (neoclassical) economics, and economic growth (as in quarterly or yearly GPD increases) are, respectively, not only inappropriate but detrimental metrics, frameworks, and goals for human and social progress today (i.e.: to define and frame future human development). In this preface: first, I contextualize the problem statement just presented above that motivates my work, to elaborate and assess the components of the National footprint Accounts (NFA), Biocapacity (BC) and the Ecological Footprint (EF), as a novel set of indicators to incorporate ecological/environmental considerations into the assessment of development at the national and global

[1] Opening paragraph of my statement of purpose to Cornell admissions completed November 2012.

levels; and second, I present the contributions of my work and explain how my approach and findings advance research, policy formulation, and praxis.

I Contextualizing the problem statement

To contextualize my problem statement, that income metrics, their *per capita* variants, orthodox economics, and economic growth are detrimental to define and frame human development, first, I provide definitions of, on the one hand, development and, on the other hand, income metrics and economic growth. Second, I describe the relationship between the two to support my assessment.

On the one hand, 'development' (as in human, social, national, regional, international, and 'economic development') is a term utilized to refer to the improvement of the conditions that determine the quality of life of the members of a community, e.g.: a region, a city, a country [3,4]. Even though, historically it has seemed impossible to achieve a unified definition of a desirable quality of human life (or it has been made to appear impossible), a minimum level of agreement may be achieved where communities that lack sufficient food, water, shelter, sanitation, education, health services, jobs, social safety nets, security conditions, and opportunities for leisure, social interaction, intellectual stimuli, and cultural expression, to avoid the preventable death (and harm) of their members, can be accepted to be 'less developed' than communities that can provide these conditions sufficiently to avoid the preventable death (and harm) of their members. This is, barring the reduction in one community of these conditions by (members of) another community (for example: through armed aggression, pollution, economic sanctions, or political intervention), in which case we should be speaking of judicial prosecution and not development.

Furthermore, as we may doubt that any community has achieved providing said conditions sufficiently to their members to avoid any death (or harm) from the absence of these conditions, we may be able to agree that a tally of the deaths and harms caused by the lack of each of the referred conditions may provide a continuous scale (or a multidimensional 'space') to localize countries along a gradient of 'development' to allow for comparison and evaluation. In this scenario, we may be able to evaluate how "income metrics, their *per capita* variants, orthodox economics, and economic growth are detrimental to define and frame human development".

On the other hand, nominal GDP is "the market value of all final goods and services produced within a country in a given period of time"[5]. Real GDP corrects nominal GDP to account for inflation (variations in the value of money due mainly to availability). Therefore real GDP is a value-based index of the aggregate production that went into the commercial consumption of goods and enjoyment of services, "It is the best index we have of total resource throughput" [6]. "The unit of measure of real GDP is not dollars, but rather 'dollar's worth'" [6], as they represent what was paid for with those dollars. GNI, formerly known as GNP, defines these accounts not by where production is located but by the location of the registration of the ownership. At the global level GDP and GNI are equivalent. Finally, the *per capita* variants of income metrics are nothing more than the presentation of these metrics divided by the population of the nation to account for the variation in size among countries and allow for inter-national comparisons.

An increase in GDP (or GNI), therefore indicates an increase in the total amount of goods consumed and services enjoyed, and because goods are consumed, and services require infrastructure that requires maintenance, an increase in GDP indicates an increase in the total inputs necessary to provide for the production of those goods and services. Furthermore, because humans are living beings and human desires most frequently require the involvement of materials, an increase in the satisfaction of the basic needs and desires of human beings predominantly requires an increase in the consumption of materials. Consider how much of all human needs and desires are 'immaterial', and how much of those immaterial needs and desires can be satisfied without material inputs [7]. For example, without infrastructure, maintenance, conditioning (i.e.: air conditioning), and food for the fellow humans involved in the provision of said immaterial needs and desires (but also, probably clothing, shelter, amenities, etc., as you would probably, prefer your service providers be clothed, sheltered, not stressed, etc.).

With one minimally agreeable definition of 'development' and definitions of GDP and GDP growth (as stand-ins for other income metrics, and economic growth), we can study the relationship between the two to establish whether or not, one (GDP) is an appropriate or inappropriate metric for the other (development). The following arguments are summarized, re-elaborated, and illustrated, departing from the work by Ecological Economist Herman Daly [6,8].

The first thing to note is that development is a qualitative change, a change that improves the determinants of the quality of human life. Meanwhile, economic growth as represented by the growth of real GDP is a change in scale, size. It is the same type of difference as the one between breaking-in new (appropriate size) shoes and getting oversized ones, getting food thoroughly cooked and getting supersized on raw food, or demanding more food, water, shelter, sanitation, education, health services, jobs, social safety nets, security conditions, and opportunities for leisure, social interaction, intellectual stimuli, and cultural expression, for those who needed them, and getting the answer that more commercial transactions (corrected for inflation) were registered last year! But how could this last answer be inadequate?

I will now proceed to present four major reasons and two codas, why income metrics and economic growth cannot be good indicators for human development.

1. Allocation. The growth of something desirable does not imply the overall growth of the economy, and the overall growth of the economy does not imply the growth of something desirable. With the current availability of products to satisfy human needs and desires and the current size of the flow of economic transactions, we do not need to enlarge the overall throughput of natural resources, labor, energy, and waste to satisfy the basic necessities of those most in need. It would suffice with allocating some resources and economic flows to those needs with minimal 'sacrifice' from other sumptuous, inefficient, or wasteful activities. Likewise, the past growth of the resource and economic flows

toward certain activities (e.g.: police militarization, increasing video games refresh rate) did not contribute to the satisfaction of any human needs.

For example, it has been demonstrated that since the ’80s, in the U.S. and other wealthy nations, increasing throughput as measured by real GDP no longer increases welfare as measured by the Genuine Progress Indicator (GPI), a variation of the GDP accounts that subtract the “costs” of production [6,9]. Similarly, “Self-reported happiness increases with *per capita* GDP up to a level of around $20,000, per annum, and then stops rising. The interpretation given is that while absolute real income is important for happiness up to a sufficiency, beyond that point happiness is overwhelmingly a function of the quality of relationships by which our very identity is constituted” [6].

2. Production has costs. These costs can be detrimental. There is abundant evidence that in many cases the detriments from the costs of production are growing beyond the benefits obtained from that production, locally in many situations: accumulation of nuclear wastes [10,11], biodiversity loss [12,13], depleted mines [14,15], deforestation [16,17], eroded topsoil [18,19], dry wells and

streams and degraded rivers [20–24], marine dead zones [25,26], informalization and precariousness of workers [27,28], and chronic indebtedness [29], and globally in a few: climate change from accumulated greenhouse gas emissions [30], sea-level rise [31], ocean acidification [32,33], gyres of plastic trash[34,35], and the ozone hole [36–38].

In technical terms, when the rising marginal costs of growth equal its declining marginal benefits, the net benefits of growth become null, and when the rising marginal costs of growth go beyond its declining marginal benefits, societies start accumulating social ills and environmental debts. The pursuit of GDP growth can be blind to issues of quality and efficiency of production (what and how to produce). Consider how market signals have been useless to avoid the emergence of zoonotic diseases from wildlife markets and the expansion of agricultural frontiers [39,40] or the recurrent market gluts that lead farmers to dump their production [41–47].

3. Market transactions are assumed to occur between willing buyers and sellers and therefore to be beneficial for the involved parties. Nevertheless, this ignores the occurrence of externalities, the

externalization of the whole or part of the costs of production (numeral 2). Externalities are negative environmental and social impacts that affect third parties and nature, by definition, not directly involved in the transaction (externalized). Furthermore, GDP counts as willing transactions (i.e.: growth) the extra costs required to avoid, mitigate, control, recover, and/or compensate, these negative impacts.

For example, GDP included as growth the costs incurred by the cleaning efforts necessary after the Exxon Valdez and the Deep Horizon oil spills [48–51], and it will count as a positive the additional costs due to the excess requirements for economic recovery, medical treatment, and funerary services which could have been avoided by opportunely adopting much cheaper public health measures focused on preserving the life and well-being of people and not the economic flows of companies, corporations, and 'economies' during the ongoing COVID-19 pandemic [52,53][2].

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[2] These early references illustrate the logic of my statement that the costs of COVID-19 are accounted as contributions to GDP. The perverse conception of health as an input to GDP, the ineffectiveness of GDP as an early signal for human wellbeing, and the *a posteriori* (after the tragedy) considerations of preventive health investments justified for the sake of future GDP growth. These issues, are illustrated with quotes from the presentation of the McKinsey Global institute Report [53], despite their laudable aims and intentions. "Overall, we estimate that the cost of ill health was more than $12 trillion in

4. Accounting for progress in monetary terms assumes very high substitutability among the factors of production, that is, it assumes that raw materials (natural resources, renewable, non-renewable and recoverable), know-how and human work are equivalent because they can be valued in terms of, and exchanged for, money (capital). Clearly, I cannot actually eat, wear, or build my house with money or knowledge, the same way I cannot, normally, exchange my clothes for food at a restaurant, pay groceries with a

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2017, about 15 percent of global real GDP. Health shocks such as the COVID-19 pandemic, H1N1 influenza, and SARS can result in additional humanitarian and economic costs. The COVID-19 pandemic and its repercussions, such as the shelter in place measures to control the spread of the virus, are forecast to reduce global GDP by 3 to 8 percent in 2020". "The economic benefits from the health improvements we size are substantial enough to add $12 trillion or 8 percent to global GDP in 2040, that translates into 0.4 percent faster growth every year". "By 2040, 245 million more people could be employed. About 60 million of them would have avoided early death from cardiovascular disease, cancers, malaria, and other causes, adding $1.4 trillion to 2040 GDP. Addressing mental health disorders, diabetes, or other conditions would no longer be a barrier to joining the labor force for an equivalent of about 120 million full-time workers, contributing an additional $4.2 trillion. Another $4.1 trillion could be unlocked by expanding labor-force participation among three groups: older populations for whom better health can be an opportunity to work longer (about 40 million people), informal caregivers who no longer need to care for loved ones (12 million people), and people with disabilities who can go to work because workplaces adapted to accommodate their needs (eight million people)". "Lastly, improving health could drive up productivity and lift GDP by as much as $2.0 trillion by reducing presenteeism from chronic conditions such as low back pain, but also through investing in childhood nutrition, which improves the cognitive and physical health of the future workforce. Just addressing adolescents' mental and behavioral health issues, which affect about 60 million young people globally, could unlock $600 billion by 2040 through raising their educational attainment and earnings potential". "While more challenging to value in dollars, we estimate the social benefits from improved health by applying the approach used in economics to measure welfare. We estimate the total combined value of deaths averted and reduced ill health could be approximately $100 trillion without adjustments for income levels—eight times the estimated GDP benefits. This number is so high because people typically value good health above everything else. Improving health could also help narrow health disparities within countries and across countries. This in turn could also contribute to reducing income inequality within countries and strengthen the social contract". "*The best part* is that focusing on known health improvements could deliver an incremental economic benefit of $2 to $4 for each $1 invested".

factoid, or obtain understanding from a pocket full of coins, a brick or a hamburger. These three substances, four including energy, flow 'together' through society and can be used interchangeably to measure each other but they have different qualities, realize different functions, satisfying different needs with different causal (and consequential) relationships. To focus on the growth of monetary transactions and assume very high substitutability, to the detriment of the other flows and stocks, creates a false sense of security and can lead us, 'unwillingly', to contaminate, deplete, extinguish, degrade or waste our sources of food, water, raw materials, energy, human work, and knowledge.

The current levels of environmental degradation and human plight, as compared to the global GDP demonstrate nature cannot be protected, natural resources replaced, and human basic needs satisfied by the faster circulation of money through 'the economy' and its higher accumulation in bank accounts (private or public).

Coda 1. Innovation may make things easier to produce, but we will still need resources to consume (inputs) and will have to deal with the waste. Even though knowledge seems immaterial and therefore infinite growth could be premised on the growth of knowledge, for knowledge to be effective it needs to be embodied in a mind that requires resources to run and, in the case of humans, it requires further resources to provide goods and services to keep us satisfied.

Coda 2. In a similar way, as long as humans' survival depends on earth's biologically based production (most critically for food but more substantively for awe and wonder, i.e.: ecosystem services) the expansion of the human enterprise into additional frontiers (such as the earth's core, the deep sea, low orbit, Mars, or outer space), will be, to put it in investor terms, 'zombie startups' with a high 'burn rate' and without a 'break-even' insight. That is, projects borrowing on the future, without a feasible plan to become sustainable and therefore condemned to bankruptcy and probably fraud charges. Economic growth cannot 'account' for the quality and amount of real resources (food, water, materials, and energy), necessary to expand humanity beyond the limits of The Biosphere (i.e.: Earth), much less if it cannot account for the sustainability and dignity of all its members in that biosphere today.

In conclusion, income metrics, their *per capita* variants, orthodox economics, and economic growth are detrimental to define and frame human development because 1. they focus on increasing societies' overall throughput (inputs, work, material, and energy and 'outputs', waste) ignoring allocation, 2. they ignore that increasing societies' concomitantly increases production costs (negative impacts), 3. they ignore that willing buyer/willing seller transactions frequently externalize negative impacts to nature and society, 4. they are obscure regarding the quantity and quality of the different kinds of substances necessary for human sustainability and dignity (food, water, shelter, sanitation, education, health services, jobs, social safety nets, security conditions, and opportunities for leisure, social interaction, intellectual stimuli, and cultural expression), and 5. they place an unsubstantiated (literally) hope on immaterial human intellect (innovation) and inhospitable frontiers (the earth's core, the deep sea, low orbit, Mars, or outer space) to provide sustenance for the enlargement of a biological and therefore, biologically dependent humanity.

Income metrics, their *per capita* variants, orthodox economics, and economic growth are so inappropriate to indicate human development that an insistence to focus on them resembles Exxon Mobil's denial of climate change science [54–59] and the tobacco industry's interference with scientific assessment and regulation [54,60–66].

Alternatively, we humans may want to monitor the quantity and quality of the determinants of the quality of human life: food (biocapacity), water (water cycles), and the (quality and quantity of) provision of shelter, sanitation, education, health services, jobs, social safety nets, security conditions, and opportunities for leisure, social interaction, intellectual stimuli, and cultural expression. With a planetary population of well over 7.5 billion people, we should certainly have enough workforce to focus on more than one indicator.

Monitoring the viability of the biosphere may be a good minimal consideration for a biologically dependent species given that in spite of uncertainties [67–69], and remaining challenges [70–72], research strongly supports the idea that biodiversity loss negatively affects ecosystems functioning [73–86], and therefore, the productivity and stability (and resilience)[3] of Ecosystems Services from which people derive benefits (e.g.: pollination [87,88], marine resources [89–92], other aquatic resources [93,94], soils [95,96], forests [97], and diseases control [98,99]). Furthermore, protecting ecological and evolutionary processes from unaccounted (and ungranted) degradation and extinction will provide time-tested and inexhaustible (self-renewing) sources for intellectual stimuli, and cultural expression (see, for example, [100–102] on the aesthetic value of biodiversity), and no ethicist has ever argued 'wanton' degradation of

[3] The content of the concept of resilience, and its distinction from that of stability is a complex technical matter, which there is no place to discuss here. The references include research supporting each.

ecosystems and 'willy-nilly' extinction of lineages of living things are morally right.

Besides all of the previous, we should probably not forget that as Edward S. Mason and Robert E. Asher put it in "the first serious, independent analysis of its activities [the World Bank's] and those of the other members of the World Bank Group-the International Finance Corporation, the International Development Association, and the International Centre for Settlement of Investment Disputes" [103], "[t]he growth of per capita GNP was put forward *simply as the best* measure of a changing life style. And changes in the life style associated with increases in per capita GNP were commonly thought of as economic development, or simply development." because "[i]nsofar as income redistribution, effects on employment, urbanization, or other factors that may affect political stability are taken into account, *they are, and should be, regarded as inputs related to an output of GNP rather than outputs* representing an aspect of development not embraced within the meaning of GNP. *This may be an inadequate concept of economic development*, but it seems to be *the only* one appropriate to the Bank and perhaps the only generalized concept to which, for the time being, definite meaning can be attached [by bankers]" (Mason and Asher 1973 [104] chapter 14 "The Bank's conception of the development process and its role therein" Appendix "A note on the meaning of development" pp. 509 and 513 respectively).

II My Contributions

Highlighting technical possibilities and recent advances to improve the quality of highly criticized, but 'important', development taxonomies, and bringing ecological and economic dynamics together to analyze development across time and space, in this thesis: 1) I demonstrate a data representation that allows the comparison of multiple nations simultaneously in terms of the components of their National Footprint Accounts (NFA), Ecological Footprint (EF), and Biocapacity (BC); 2) I test statistically the trends of these NFA components over a 50+ year period; 3) attending to critiques of existing development classifications, I demonstrate a transparent and simple clustering procedure, grounded in theory regarding both the content of the analysis and its technical execution; and, 4) I apply the most advanced techniques available to assess the robustness of the resulting classification. Furthermore, I discuss the comparison of my classification with that of the World Bank based on Income *per capita* (WBIC) and the geographic distribution of the obtained categories Thus, this work foregrounds sustainability concerns and can stimulate creative analysis of the world's most pressing challenge, global environmental change (GEC).

My study builds on the criticism of existing development taxonomies, on the work and criticism behind the development of the NFA, on previous attempts at developing taxonomies for this accounting system, on the development and recent advancements of cluster analysis techniques, and on contemporary debates within structural human ecology (SHE) and the macro-comparative sociologies of the environment and development (MCSED). This thesis makes three types of contributions, technical, theoretical, and political.

The technical contributions are, i) introducing multi-scale bootstrap re-sampling, ii) advancing 'reading the dendrogram (clustering tree) structure', and iii) recovering classical hierarchical clustering with Euclidean distances and single linkage. I contend that the transparency, simplicity, straightforwardness, and "optimal theoretical [mathematical] properties" of classical hierarchical clustering with Euclidean distances and single linkage, contribute to interpretability.

First, multi-scale bootstrap re-sampling (MSBRS) is a statistical technique that replaces partitioning for the assessment of 'clusters' and clustering results [105–108]. Partitioning implied 'cutting' dendrograms at a unique ‘distance’. Alternatively, MSBRS computes the approximately unbiased probability (AU), along with the corresponding standard error, that a cluster occurs within a dataset for all clusters in the dataset (i.e.: non-terminal branches or edges in the tree). Then, MSBRS provides a metric of the statistical support of each cluster and, therefore, along with other traditional statistical criteria (e.g.: sample representativity, dataset precision, etc.), a metric of the statistical confidence. MSBRS allows computing 95% confidence intervals for the AU that a cluster occurs.

Second, MSBRS helps advance the proposition highlighted and discussed by Milligan & Hirtle ([109], citing [110]) that “clustering and trees themselves can be models of proximity relationships, rather than the result of an algorithm for fitting data”. This is, clustering trees describe the relations of difference and similarity among items (entities, objects) in a dataset. In this thesis, I argue that we want to use these descriptions to understand the world ‘as it is’, or at least as it is described in our datasets, instead of fitting it to presuppositions. This is what I have referred to as ‘reading’ the tree structure. Despite Milligan being, arguably one of the best-regarded hierarchical clustering experts (see his [111], and [112,113]), this proposition has not yet taken hold in practice, which has been recently overtaken by computer-intensive, un-supervised, machine learning (theory blind) approaches [113–115].

Third, introducing MSBRS and advancing 'reading the tree structure' contributes to recovering classical hierarchical clustering, which is the appropriate exploratory data analysis to "separate individuals or observations into classes or groups" [109]. Furthermore, I advance Euclidean distance and single linkage for being the simplest and most transparent distance and method (the straight-line, and the shortest distance measured directly between entities in the dataset), attributes that I believe are desirable for data analysis with implications for public policy. Even more so because as Milligan & Hirtle [109] explain, "[a]n empirical classification will contribute to the knowledge of a scientific domain only if it can be interpreted substantively".

Moreover, even though single linkage has "consistently performed poorly [in Monte Carlo simulation studies]" [109,111], it has also been consistently identified as having "optimal theoretical properties" [109,111–113]. This apparent paradox is resolved if it is recognized that single linkage, performed 'poorly' when it was assessed with the improper 'partitioning' technique previously mentioned, forcing data to conform to arbitrary *a priori* assumptions. In favor of this position, I argue that the sensitivity of the method to outliers is a reflection of the fact that, due to its mathematical properties "it is one of the few clustering algorithms that would be able to detect clusters that are the result of a long chain of points, rather than a densely packed cluster of points" [109,116]. Given that in a clustering context, "outlier refers to an entity that does not fall within the general region of any cluster" [109], outliers are entities expected to affect the clustering and are common in development and in other 'natural' datasets.

The theoretical contributions of the thesis are two i) advancing a method and identifying 'regions' for SHE and MCSED, and ii) the regions identified will be useful to probe the 'role of population'. In recent publications devoted to highlighting the frontiers of SHE and MCSED, two prominent authors Thomas Dietz and Andrew Jorgenson indicated that and "important contribution" was "to point us towards heterogeneity across nations" [108 referring to 109], furthermore, they characterized the analysis of regional subsets of nations, as "an emerging methodological approach", "attentive to structural variations across nations" [110 referring to 111]. With this in mind, the methodological approach in my thesis to the dynamics of socioecological sustainability, explores in detail the classification of the joint trajectories of the components of the NFA of nations identifying shared patterns, discussing their commonalities and variation, their implications and their geographic location, i.e.: identifying and describing regions. These regions can be probed latter in more depth to further our understanding, not only of the variation of the relative strength of the drivers of GEC but also how such variation may be the result of interactions among those (geopolitical) regions of the world.

Moreover, to the extent that regions may be useful to advance our understanding of the relative strength of the drivers of GEC, they will provide a key stepping-stone to improve our understanding of the 'role of population', an issue that has marred the fields of SHE and environmental sociology and impeded progress on the implementation of policies that might help mitigate the pressures and impacts of GEC (e.g.: carbon taxes and imperialism reparations). The role of population change has become a Malthusian smoke-screen that diverts attention from progress in the field. First, as long as all nations are treated as variations of the same regression equation, population growth will always play a 'unique' prominent role regarding GEC. That is, an artificially unique role due to the absence of consideration of i) the notable variation observed of the relationship of population change to change in consumption (affluence e.g.: GDP or EF), ii) the variation in the patterns of population change among countries (time-series), iii) the partial independence of the relations of population growth to

BC and EF, and iv) without reference to the role that geopolitical relations may play in determining those patterns. Second, the frequently racist argument that 'the high population growth of those countries' is at the root of all global environmental problems will continue to distract attention from the more nuanced results in the field and from the need to understand in sufficient detail the situation of each nation (and community) in reference to the broader geopolitical context. Third, scholars investigating these issues will continue to be labeled and dismissed, or their contributions minimized, by identifying them as Malthusian (or neo-Malthusian) without substantial engagement with their work.

Finally, this thesis makes two political contributions. I have labeled these contributions political because, as it has been reiterated on multiple occasions, 'scientific knowledge' cannot be politically neutral in matters of the 'human sciences' [112–114 and 115 for a counterpoint]. The consideration of the causes of GEC, extensively identified as the increase of human pressures on the 'natural' environment and associated 'negative impacts', with an explicit emphasis on the relative strength of population, affluence, technology, and organization (SHE and MCSED) is clearly a matter of the human sciences. SHE has made great efforts to describe objectively the relationship between environmental impacts and their drivers, nevertheless, this objective exploration becomes innocuous to avoid the worst consequences for the damage and loss of property, the harm and death of people, the degradation of ecosystems, and the extinction of species if it does not imply political (democratic) mobilization [125–127]. The detailed understanding of the causes of socioecological unsustainability is nihilistic if it is not intended for the avoidance of human suffering and the destruction of nature [128].

In the latest review of the achievements of SHE and related traditions, Thomas Dietz acknowledged that "[t]he frameworks for assessing drivers of [environmental] stress are sometimes criticized for not paying enough attention to power and issues of political economy" [129]. Moreover, in his discussion of the issue, he conceded that "although it is not surprising that the overall frameworks must be rather general, *it is* equally *true that most applications of them are limited in what they consider*". He attributed this result to "a failure of theoretical imagination" [129].

My thesis pursues an objective exploration of the dynamics of the components of the NFA trough clustering and classification of features derived from time-series. It investigates the relationship of the patterns discovered to the WBIC as a stand-in for modernization theory and it points to questions and resonances with, the alternative, dependency/core-periphery/world-system theories, to the extent of its limited engagement, it finds both theoretical frameworks wanting. Echoing previous results in SHE and MCSDE, Modernization theory may deserve a deeper critical engagement to explain its function as a justification (not an explanation) of the state of things [130–134], meanwhile, the alternative framework, certainly invites further empirical engagement. Furthermore, in the search for relevant theoretical concepts, it invites the emerging literature on *extractivismo* and it indicates, where granted by the evidence, the potential for productive engagement with notions of unequal exchange, unequal ecological exchange, convergence/divergence, 'the environmental efficiency of well-being', and ecological debt.

Finally, through the technical elaboration, and through the interpretation and discussion of the results, this thesis demonstrates how the time series of NFA components BC and EF can constitute an important alternative and/or complement to income *per capita* metrics (GNI, GNP, GDP), their corresponding classifications (WBIC), and their necessarily limited (orthodox) economic frameworks, for the study of human development, specifically, through the incorporation of concerns about socioecological sustainability.

CHAPTER 1 EDITORIAL NOTE

A previous version of the document included in this thesis as chapter 2 was submitted on June 13, 2019, to the journal PLOS One. A "revision required" decision followed on August 20, 2019. The reviews were very positive and encouraging, with the academic editor stating: "[b]oth reviewers including myself saw merit in your work and we all think it's a topic worth publishing". Unfortunately, due to the scope of the paper, the diversity of interests of the academic editor and the reviewers, and to 'technical difficulties'[4], the suggestions were multiple and varied. The academic editor acknowledged, "although reviewer 1 labels his/her review as minor revisions, addressing those can be major and significantly improve the manuscript". On April 1, 2020, the journal accepted the withdrawal of the submission, as I decided to produce a completely new version of the paper, to better harmonize my improved understanding of the issues and the suggestions by the academic editor and reviewers.

During May 2020, as I progressed on the document, I identified a technical problem that had slipped me, and all reviewers involved. In my

[4] Due to 'unknown' procedural differences I would have had to re-produce all figures to comply with the technical specifications of the journal (i.e.: improper rendering).

ethical and professional opinion, this technical problem precludes the academic publication of the paper 'as is'.

Almost concurrently but independently and, under the circumstances of heightened uncertainty brought on by COVID-19[5], on June 16, 2020, Dr. Steven Wolf PhD and I agreed that I could present and defend my paper on the "agreement that your current draft [from June 13, 2019] meets the standard of a MS thesis, as it is a 'publishable paper'.", And, initiated the procedures for my readmission.

Due to the confluence of these situations, the paper included in chapter 2 of the present thesis corresponds to a partially improved version of my June 13, 2019, submission to PLOS One, including the aforementioned 'technical problem' which I describe in chapter 3. This version adequately represents my proposal, methods, and theoretical framework. And, it is worth noting that, as it is described in chapter 3, the 'technical problem' does not affect my conclusions. Nevertheless, given my learning from the review process and the necessity of correcting the 'technical problem', it will be another, future version of this paper that will stand as a contribution to the academic literature.

[5] Pandemic of a disease caused by a virus (SARS-CoV-2) that became apparent in December 2019

CHAPTER 2 DYNAMICS OF SOCIOECOLOGICAL SUSTAINABILITY BASED ON NATIONAL FOOTPRINT ACCOUNTS (1961-2014)

1 Introduction

There is a growing concern with the usefulness of development taxonomies [135–140]. Development taxonomies are classifications of countries created by international organizations and used to understand and promote notions of human progress [138,139]. In a conclusion which has enjoyed acknowledgment within the subject area, Nielsen [138,141] stated:

> "Existing taxonomies suffer from lack of clarity with regard to how they distinguish among country groupings. The World Bank has not explained why the threshold between developed and developing countries was a *per capita* income level of US$6,000 in 1987 and US$12,475 in 2011 (nor the principles, if any, that have guided the adjustment over time). The [United Nations Development Programme] UNDP does not explain why the ratio of developed and developing countries is one to three and as for the IMF it is not even obvious what it is that is not explained".

The consequences of these concerns are important for our understanding of development. For example, Vaggi [140] demonstrated that if the World Bank's 2015 thresholds were "readjusted in a way that is coherent with world economic growth", the number of countries identified as High-Income would drop from 79 to 59, while the developing countries category would increase from 138 to 158. The correction goes in the opposite direction of the expectation under the most optimistic assumption of progress. Furthermore, that effect is the result of the growth of the Low-Middle-Income Countries (LMIC) category from 52 to 62 and of the Low-Income Countries (LIC) category from 31 to 46, at the expense of the Upper-Middle Income Countries (UMIC) category. According to Vaggi [140] "the revised thresholds now provide a more moderate view of these achievements", that is, the achievements of economic development relative to 1987. To be clear, the corrected classification thresholds suggest the success of 'development' has been less (or much less) than advertised for as many as twenty nations.

Concerns about development taxonomies are especially acute for those that show, i) overdependence on economic indicators, specifically *per capita* income metrics (i.e.: Gross National Product –GNP, Gross Domestic Product –GDP, Gross National Income –GNI), ii) expectations of linearity (more income = more development), and iii) expectations of persisting absolute categories (e.g.: developed). The main reasons for concern with these taxonomies, is their poor theoretical development, for example, regarding the arbitrariness of the categories being distinguished, the indicators used and the thresholds employed [135,137–140].

In the case of overdependence on income *per capita*. It has been acknowledged that it reflects a unidimensional understanding of development. Such understanding has been called into question by the proposition of multidimensional concepts of human-social progress and wellbeing [137,139,142–146]. The over-reliance on income *per capita* metrics and economic growth has been thoroughly criticized from an environmental sustainability perspective [8,9,147–152]. For this reason, environmental sustainability along with other dimensions (e.g., democratic participation and improved governance, human development, equity, state capabilities or fragilities, subjective well-being, and structural transformation) have been suggested [137,139,142,143,146]. Incorporating environmental sustainability into a multidimensional concept of human-social progress and well-being requires identifying appropriate metrics to assess the consequences on environmental conditions of current human-social progress and wellbeing for the human-social progress and wellbeing of future generations.

The National (Ecological) Footprint Accounts (NFA) constitute a widely recognized sustainability 'metric' [153–161]. The availability of NFA datasets with broad temporal (53 years) and geographic (over 140 countries) coverage [162] supports extensive analysis by environment and sustainability scholars [120,163–171]. NFA analysis has a well-known, even though, delimited policy relevance [172–175], and applied to ecological sustainability, it is "doubtlessly one of the most powerful tools in public communication" [176]. NFA, are not the only sustainability metric conceivable, available, useful, or necessary but it is available, valid, and useful (see [177] for an update on applications). Today, Ecological Footprint and its components have significant institutional acceptance as they constitute an important share of the "core indicators selected for use in [the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services] IPBES regional assessments and global assessment" [178]. In the present investigation, I advance the study of the NFA. However, in light of the growing recognition that no single metric can satisfy all the information needs of a complex subject matter, and that a 'dashboard' of indicators may be desirable instead [149,152,179–183], it is necessary to keep working on a variety of independently developed and maintained, successful indicators, which contribute to our understanding of social progress (e.g.: sustainability, life satisfaction, well-being, equity, biodiversity conservation, etc.).

In this paper, I respond to what Andrew Jorgenson and Thomas Dietz writing from the traditions of environmental and development macro-comparative sociologies and from Structural Human Ecology (SHE), have identified as a "recent", "emerging" and "important contribution": being attentive to the heterogeneity of the structural drivers of environmental change among regional subsets of nations [117,119]. This is, taking into consideration that the effect of the main factors of global environmental change (GEC), may vary among different regions of the world, see: [118,120].

Nonetheless, I take a step back from the analysis of the relative contribution of factors of GEC. And, alternatively, focusing on the dynamics of the component of the National Footprint Accounts, Biocapacity (BC) and Ecological Footprint (EF), using *per capita* terms suitable for international comparison, I investigate a question that should receive priority when considering the selection of subsets of nations or 'regions'. "Is there evidence for asserting the existence of different categories of countries? (i.e.: different groups, types of countries, or 'regions'). From the answer to this question, I obtain an answer to a second question: "Which countries belong to which groups?". And consequently, I elaborate on a third question "How can these differences be interpreted?".

To achieve this, attending to the critiques of existing development classifications, I demonstrate a transparent and simple clustering procedure, grounded in theory both regarding the content of the analysis and technical execution, and, I assess the robustness of the results using recently developed techniques (multiscale bootstrap re-sampling). I formulate an international 'sustainability' classification, and I discuss my results in light of the results of previous contributions and alternative development theories. In particular, I compare this classification with that of the World Bank based on Income *per capita* (the dominant stand-in for modernization theory), I discuss my results in relation to the alternative dependency/core-periphery/world systems theories, and, I describe the geographic distribution of the categories obtained. I tentatively point toward the budding literature on *extractivismo* (extractivism) as an opportunity to articulate the achievements of previous development theories and the observations that derive from my contribution. Finally, I critically assess the resulting taxonomy and I point toward opportunities for future methodological improvement.

With the aim of contributing to the debate about international development taxonomies and to the ongoing conversation on human-social progress and wellbeing, more broadly. The taxonomy that I introduce, contributes to re-framing social progress from a notion of unbounded accumulation of wealth to a notion of political, uneven contest concerning people and natural resources. It does this by creating an opening to engage with social issues like widening and narrowing differences among nations (convergence/divergence), environmental or ecological (in)efficiency, unequal exchange, unequal ecological exchange, and ecological debts.

1.1 NFA taxonomy antecedents

Two taxonomies have been elaborated using the NFA. On one hand, Sturm *et al.* [184] identified multiple dichotomous conceptual classifications for 44 countries for an analysis bridging competitiveness and sustainability using data for 1993. The most appealing distinction from that analysis, that between ecological "creditors" (BC>EF) and "debtors" (EF>BC) [6], has been used in publications aimed at the general public by the Global Footprint Network–GFN [185]. On the other hand, Niccolucci *et al.* [168], classified the jointed trajectories of national Biocapacity *per capita* (BCP) and Ecological Footprint per capita (EFP) by "trend similarity". They used this classification along with a nation's Population, Environmental Sustainability Index (ESI), Environmental Performance Index (EPI), and Human Development Index (HDI) to produce "sustainability profiles" and to suggest a geopolitical interpretation "highlighting the fundamental role of Biocapacity".

[6] *"By analogy with terms commonly used in economics, we refer to one category as 'ecological debtors' and the other as 'ecological creditors.' This analysis reveals which countries live at the cost of others and which countries make their remainder of natural capital available to others (the selling countries, or, in economic terms, the creditors)"* [184]. A further, necessary distinction between 'willing' debtors and 'indebted' countries is introduced in section 2.7

NFA data presents an exciting opportunity to analyze development across time and space because the focus on ecological and economic dynamics brings sustainability concerns to the foreground. Nevertheless, existing applications are unsatisfying because they are either static and/or too inclusive (coarse), failing to distinguish types of creditors and debtors, as in the case of Sturm *et al.* [184], or because the discriminant criteria do not work as reported, and the classification is highly dependent on additional indexes, as in the case of Niccolucci *et al.* [168].

The present contribution focuses exclusively on NFA to better understand their behavior. Steps are taken to incorporate into the classification more of the information available in the NFA dataset, than in previous efforts. And, cluster analysis and the assessment of uncertainty through multiscale bootstrap re-sampling are implemented to elevate the objectivity and statistical robustness of the process of classification. Nevertheless, this contribution is built on the learning achieved in previous work to offer the foundation of an analytical tool to help animate and inform future debates. By looking at the registered history of supply and demand of nature's regenerative capacity, we can identify the paths to (un)sustainability [117], and, hopefully, respond to the challenge. The NFA public dataset [162] is one reasonable place to begin this exercise.

2 Materials and Methods

This section explains, i) the interpretation of the *per capita* components of the NFA that I advance; ii) statistical test of assumptions preliminary to the formulation of 'models', iii) the decisions involved in the selection of 'models'/representations of the trajectories of the NFA before clustering; iv) the decisions involved in the clustering procedure; v) taxonomic nomenclatural details; And, vi) the schema followed for the interpretation of the clustering results.

2.1 Interpreting the NFA

NFA are an accounting system that provides information on one important aspect of sustainability. This has been referred to as the 'ecological balance', the (accounting) balance between the supply and demand of "earth's regenerative capacity" [155,186]. The NFA time-series allow us to observe the change in the components of this balance over time. In this paper, I treat the joint trajectory of the components of the NFA, BCP (supply), and EFP (demand), as representing this important aspect (ecological balance) of national environmental policy. This is, how does the environmental consumption nominally available to a country's citizen change (increase or decrease), with respect to changes in the nominally available domestic biological production for that 'same' citizen?

Therefore, instead of assessing, national policy documents, laws, speeches, party platforms, and slogans, authored by, elected officials, legislators, government officers, politicians, other public figures, and social movement leaders, and, instead of pooling and surveying constituencies, to see what they all intended or claimed to do, I suggest looking at the registered data to understand what the actual consequences of decisions and behaviors have been. Hereinafter, I refer to the joint trajectories of the components of the NFA, BCP, and EFP, as trajectories or policies interchangeably.

Appendix 1 provides a brief discussion of the NFA as a tool for tracking sustainability, including a comprehensive review of academic references on its limitations.

2.2 Trend Analysis

Following Niccolucci *et al.* [168], who identified most NFA time-series with simple trends, and my own extensive observations on the NFA. I decided to test statistically (to execute the best possible attempt to falsify), the assumption that the time-series follow simple trends (ascending, descending, or stationary).

Therefore, trend analysis assessed two assumptions: i) that neither the initial nor final value of each variable constitute outliers and ii) that the time-series for each variable cannot be adequately described by strongly concave or convex functions. The following statistical tests were performed to each time-series: Box-Ljung (autocorrelation), Mann-Kendall (monotonicity for not auto-correlated time-series), Hamed and Rao's correction to Mann-Kendall (monotonicity for auto-correlated time-series, [187]), Spearman Rank correlation (Monotonicity), Philips-Perron (stationarity, i.e.: unit-root test), Kwiatkowski–Phillips–Schmidt–Shin (known as KPSS, for trend-stationarity) and the time-series outliers identification process by Chen and Liu [188].

2.3 'Models'/representations of the NFA trajectories

With the results of the trend analysis, I decided to use a simplified description of the joint EFC and BCP trajectories for each country. This simplified description corresponds to a line-segment defined in a two–dimensions orthogonal coordinate system (an XY-plot). In this coordinate system, the x-axis corresponds to BCP and the y-axis to EFP, and each line-segment connects two EFP and BCP coordinates, one at the beginning and one at the end of the period of analysis.

For the cluster analysis, each line-segment was described using four variables (Figure 1): The EFP and BCP coordinates at the end of the period of analysis (EF_f and BC_f), the length of the segment or trend length (Tl), computed using Pythagoras' theorem; and, the slope of the segment (θ), expressed in sexagesimal degrees, obtained by computing the arctangent of the slope of the segments expressed in term of the Cartesian coordinates. The latter was achieved by 1) translating the line-segment for its origin to coincide with the origin of the coordinate system, 2) applying Microsoft Excel's *ATAN2* function to the coordinates corresponding to the 'last year' of the translated segment, 3) multiplying the result by (180°/π), and 4) adding 360° to the negative results from the previous step (Figure 1D). The present analysis can be understood as an application of features-based time-series cluster analysis [189,190], where each country is modeled using one linear equation (not a function) to represent two time-series simultaneously, and features are extracted from the resulting model.

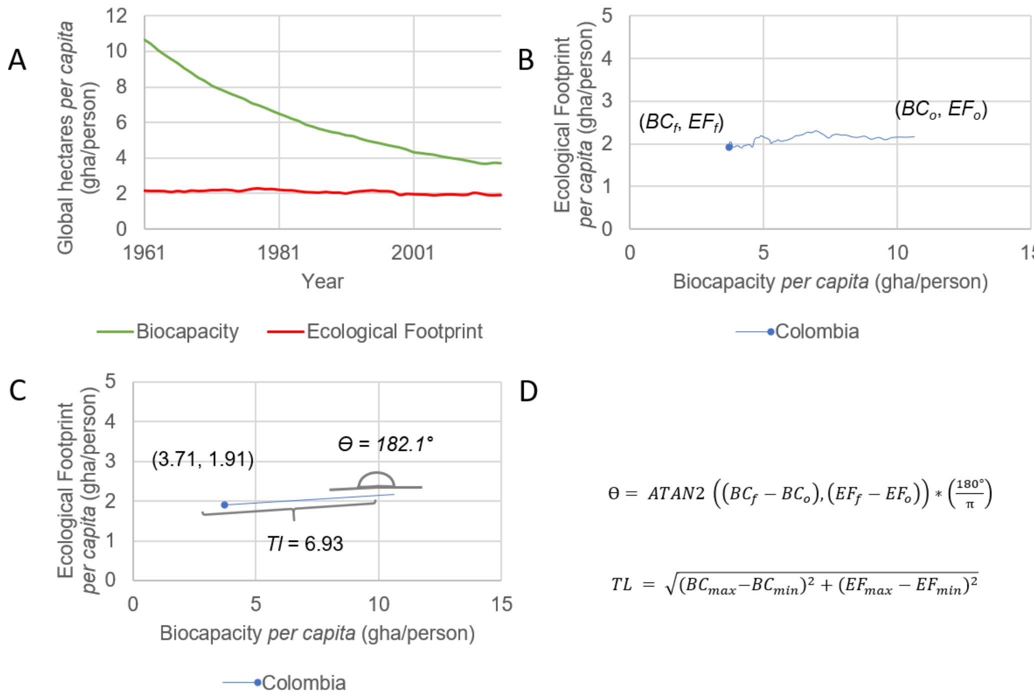


Figure 1 Representations of original and processed data
Data for Colombia are used in all steps of the example: **A**. Original data: 'Country plot' for Colombia reconstructed with data from [162]; **B**. Joint trajectory of EFP and BCP, initial and final coordinates are indicated; **C**. Line-segment with four describing variables indicated (features); **D**. Equations for Θ and Tl (see text). **Note**: An enlarged dot marks the last year of the study period, 2014. Consequently, the opposite end (unenlarged) corresponds to the first year, 1961.

The costs/risks of using these (linear) models are overemphasizing linearity, dismissing the uncertainty revealed in the year-to-year variation of the time-series, and over-trusting the representativity of the first and the last years. To minimize these negative effects, my discussion and conclusions are based and limited to, general trends and patterns, de-emphasizing specific values and an assessment of their precision. Instead, I focus on thresholds, supported by gaps that are 'large' relative to the variation within the dataset.

2.4. Software

Trend and cluster analyses were performed in R Foundation's R [191]. Data preparation and statistical outputs were elaborated in Microsoft's Excel and R. Kernel density estimates were obtained using the U.K.'s Royal Society of Chemistry Excel Add-in [192,193]. Cartography was prepared in ESRI's ArcGIS.

2.5 Data sources

EFP and BCP were obtained from the Global Footprint Network [162], income classification from the World Bank [194], and the cartographic base from Natural Earth [195].

In section 3.2.1, bioregions refer to the biomes in [196]. In this paper, I prefer the term bioregion to the term biome as it may be understood by a broader audience. Countries in the same bioregion are in the same biome or in a mosaic of biomes of similar composition. Countries in equivalent or similar bioregions are found in mosaics of biomes of similar structure but slightly different composition or in biomes that are contiguous along ecological gradients (e.g.: moist and dry broadleaf forests in tropical and subtropical areas). The territories of countries in equivalent bioregions are more similar between them than the territories of countries in similar bioregions. Distances between capital cities were obtained from [197].

2.6 Cluster analysis

The "methodological approach to applied cluster analysis" presented by [111] was followed by incorporating the recommendations formulated by [109,112,113] who advanced this approach. The decisions made to adjust each step suggested by [111] are described below.

The objects (entities) included in the cluster analysis were the 123 countries with data available for the period 1961 – 2014 in [162]. The variables included in the analysis were the four variables that characterize each line-segment which describes the joint trajectory of BCP and EFP of each country (EF_f, BC_f, Tl, and θ). Variables with the same units, i.e.: global hectares *per capita* gha/person (EF_f, BC_f, and Tl), were standardized together using their combined range (overall maximum to overall minimum), while θ was standardized on its own. In both cases standardization was achieved by '0 -1 scaling' i.e.: (X – Min/(Max-Min)), where X is the value being standardized, and Min and Max are the minima and maxima of the corresponding range. There were no missing values in my dataset.

The Euclidean distance was used for the proximity measure. A Euclidean distance corresponds to a straight line between two points. Euclidean distance was preferred because it is straightforward to understand, and it can be applied to a multidimensional space that has no known constraints. Single linkage was selected for the clustering method. Single linkage "operates directly on a proximity matrix" [112] and joins entities (single entities or clusters) by the shortest distance between them, it uses a nearest-neighbor (a friend of friends) criteria that can be directly mapped to the minimum spanning tree (MST). It has been argued that single linkage "possesses optimal theoretical properties" [111,112]. Finally, the uncertainty of specific clusters (bundles of branches that share a node) was assessed by the approximately unbiased (AU) probability estimates ('p-values') provided by the R package 'pvclust' [107,198], which performs multiscale bootstrap resampling [105,106,199].

2.7 Taxonomy and nomenclature (labels)

My taxonomy corresponds to the results of the clustering analysis. I label the resulting branches C1 to C15. I only introduce two terms to refer to two major processes: Negative Balance Trade-Off (NBTO) and Positive Balance Trade-Off (PBTO). Nevertheless, I analyze, modify, and apply category labels from previous taxonomies because they are informative and have historical value, and to understand the relationship of those taxonomies to my results. I refer to these labels as 'sustainability labels'.

I use the term sustainability in a lax sense even though it has been agreed that in a strict sense the ecological balance, that is the difference of the BC to the EF at the national level (or the BCP to the EFP, using *per capita* terms), more narrowly, indicates the ecological self-sufficiency of that nation/territory [200–202]. Table 1 contrasts the labels used in previous taxonomies and in the present work and introduces my sustainability labels.

Table 1 Sustainability labels

Sturm *et al.* [184]	**Niccolucci *et al.*** [168]	**This work**	
		Process	Label
Creditor	Parallel and Wedge	Biocapacity reserve	Historical creditor
Debtor	Scissor	Transition to unsustainability	Recent debtor
		Biocapacity deficit	Historical debtor
Creditor or debtor (depending on the balance of the last year)	Descent	Any of the other four processes when both BC and EF decline simultaneously	Historical creditor, or debtor, or recent creditor, or debtor (depending on the balance of the first and last years)
N/A	N/A	Transition to sustainability	Recent creditor

Summary of contrasts of previous taxonomies and the present work

The following observations can be made about table 1:

1. The categories from Sturm *et al.* [184] are represented inconsistently in the classification by Niccolucci *et al.* [168].
2. Relating to the categories of [168]:
   2.1. 'Parallel' and 'wedge', are unclearly or, erroneously distinguished
   2.2. 'Scissor' confounds two distinct patterns (considering the criteria applied for other categories by the authors)

2.3. 'Descent' introduces an additional criterion, not applied consistently in other categories, and therefore, overlaps with other categories. Appendix 2 provides a more elaborated discussion of the inconsistencies in [168]

3. Regarding the present work:

3.1. Most of the categories by [168] can be understood as describing the process of change of the 'last-year-static categories' provided by [184], by considering the beginning of the time-series. For example, 'parallel' and 'wedge' describe creditors that did not change in status. Likewise, 'scissor' describes debtors which were either creditors or debtors at the beginning of the period.

3.2. I created four compound names for these categories: 'historical creditors' (creditors for the whole study period), 'historical debtors', 'recent debtors' (became debtors during the study period), and 'recent creditors' (these countries were debtors at the beginning of the study period and became creditors by the end of it). Note that, the last category was not identified, nor present in the data, for the studies by [184] and [168].

3.3. A distinction between willing debtors and nations that were 'made' indebted, if it exists (e.g.: as a consequence of colonialism, neo-colonialism, terms of trade, etc.), is desirable. Nevertheless, the methods by [168,184] do not allow to probe this issue. My methods open up this possibility which is elaborated in the discussion.

3.4. Only in one case, deviation from these four categories was notable. This is the case of Norway, which was a creditor in 1961, a debtor in 1966, 1967, 1970 – 1979, and 1988, and then a creditor again afterward. Other countries may have had brief oscillations of ecological balance (usually around transitions) which nevertheless do not affect their overall trajectories. The data from Norway were treated as those of every other country in our analysis, nonetheless, these and other minor variations (i.e.: change of the rate of change), call for further analyses which are briefly discussed in section 3.1.

3.5. I applied these categories consistently to all countries in the database.

3.6. Finally, it is worth highlighting that the systematic data processing and statistical analysis presented in this paper, replaces informal criteria used or suggested by [168], such as, the direction of the trajectory of the variable.

2.8 Interpretation

A description of the characteristics and internal variation of each cluster was produced. A contingency table was elaborated to contrast the distribution of clusters and sustainability labels to the World Bank's 2014 analytical classification [194], and the geographic distribution of the categories was mapped.

3 Results and Discussion

3.1 Trend analysis

Trend analysis of the NFA confirms at the national level the well-recognized observation that for the most part, major human institutions (nation-states, global governance institutions, major businesses and business-networks) and aggregate consumer behavior, have been going 'business-as-usual', despite numerous and substantial calls to revise and reform practices to pursue environmental sustainability. The selection of line-segments as simplified descriptions of the joint trajectories of EFP and BCP constitute adequate characterizations of those trajectories in all but one case. The Ecological Footprint of Jamaica has a 'light' upward trend, consistent with its later classification, but it is unstable (affected by year-to-year variation). This can make the classification of Jamaica unstable, oscillating between two clusters, nevertheless, this occurs between the two largest clusters (C10 and

C12), which are also among the closest (and share historical, economic, and geographic characteristics, compatible with Jamaica). Therefore, line-segments are adequate characterizations for all but one trajectory, with minimal consequences for the classification in general, and for that exception. An extended description of the results of the trend analysis is included in appendix 3.

The previous statement does not imply that there were not minor or temporary variations in the direction of particular trends, that there were no variations in the rates of change over time, that relatively large changes for a particular country (but not for the database) did not occur in one country, and especially, that large changes could not have occurred in countries not included in the dataset analyzed. The present analysis says nothing about the variation in the rates of change of BC and EF *per capita* over the study period, and visual inspection of the data makes it obvious that these changes in rate are present. Nevertheless, this result does suggest that the effects of the variations in the direction of trends for cluster analysis of these trends will, most probably, be subordinated to the clusters identified in the present study. This is because, given thermodynamic constraints of 'real-world' systems, historical trajectories between the same starting and ending point should be more similar among them, despite their 'sinuosity', than similarly sinuous trajectories between different starting and ending points. This is, the same way that 'reasonable' (routes were one ultimately arrives at destiny without incurring unreasonable energy and wear inefficiencies, even though not necessarily optimal), routes between Paris and Rome should be more similar, among them, than routes between Paris and Berlin (or Port au Prince and Havana v. Port au Prince and Miami).

A different issue would arise when trying to distinguish between 'reasonable' routes between the north of city A and the south of city B and routes from the south of city A and the north of city B (i.e.: very small differences in origin and destiny). The discussion in section 3.6.1 regarding transformations and standardization corresponds to these issues of the differential weighting of distances in different locations.

3.2 Cluster analysis

The multiscale bootstrap resampling procedure [198], identified 78 clusters with approximately unbiased probability estimates (AU) higher than 0.9. Of these, 48 have AU higher than 0.99. This means that there is a chance higher than 90% or 99% respectively, of identifying these clusters when selecting random subsamples within the dataset and incorporating the information gained at each level of clustering ([106] and references therein). Therefore, all those clusters suggest there may be important similarities between the countries grouped regarding the processes that determine the simultaneous change over time of BCP and EFP, accordingly, all of them are worthy of further study. Complete clustering dendrograms with and without AUs can be found in appendix 4.

3.2.1 Example of highly supported binational clusters

The multiscale bootstrap resampling procedure identified twenty-eight pairs of countries (binational clusters) with AU higher than 0.9. Of these, eighteen have AU higher than 0.99. Table 2 list these eighteen pairs of countries in ascending order according to the distance between capital cities.

Table 2 Binational clusters with AU higher than 0.99

Countries		Distance between capital cities (Km)	Observations
Finland	Sweden	397	Neighbors
Portugal	Spain	503	Neighbors
Bulgaria	Hungary	630	Same bioregion
Dominican R.	Jamaica	727	Same bioregion
Ghana	Sao Tome and Principe	962	Same bioregion
Cyprus	Iran I.R.	1638	Same bioregion
Colombia	Peru	1871	Neighbors
Kenya	Zimbabwe	1936	Same or equivalent bioregion
India	Sri Lanka	2420	Neighbors
Cameroon	Mozambique	4006	Similar or equivalent bioregion
Benin	Yemen	4643	Similar bioregions [1]
Cabo Verde	El Salvador	7061	[2]
Burkina Faso	Haiti	7586	[2]
Barbados	Lebanon	9673	Equivalent bioregions [1]
Cambodia	Togo	11364	Similar bioregions [1]
Indonesia	Mali	12856	[2]
Korea R.	Trinidad and Tobago	14594	Similar bioregions [1]
Australia	Canada	15860	[2]

Countries are listed alphabetically within clusters; neighbor countries share borders. [1] I have deemed the countries in these clusters, in similar, or equivalent bioregions despite the great distance between them. [2] The countries in these clusters occupy contrasting bioregions of the world.

Physical geography (location, bioregion, and distance) seems overwhelmingly important to explain the formation of the clusters in Table 2. Fourteen clusters there (seven-ninths) correspond to neighbor countries or to countries found in the same, similar, or equivalent bioregions of the world. In some cases, the bioregions those countries occupy are strikingly similar (table 2 note 1) despite the great geographic distance between countries. In the four remaining clusters (two-ninths), physical geographic contrast tends to increase with the distance between countries. There, similarities regarding the dynamics of population density and income *per capita* (which together can be interpreted as proxies for 'mode of production', i.e.: 'level of development' and economic throughput), seem to become more important than physical geography to explain the similarity. Relying on additional information from the classification that will become apparent later in the paper (second half of section 3.2.4), differences among binational clusters seem to relate to the moment in a sequence when historical processes reach each country. That is, differences seem to be explained by when geographical locations are 'reached' by a particular 'stage' of (capitalist) development. Ideological/organizational differences, i.e.: 'political systems', do not seem to play a relevant role either in the similarities between countries or in the differences among these clusters. And, ideological/cultural characteristics, cannot be unambiguously defined to the point that they are not so indeterminate and flexible that they are not meaningless (consider the cultural 'similarities' and 'differences' between any two pairs of clusters in Table 2).

The similarities of the NFA trajectories of the binational cluster formed by Australia and Canada, two ecological contrasting countries, and the most separated pair, illustrate well the case for political-economic history. Both countries are late-independence British 'new world' colonies and, contemporary High-Income countries (according to the World Bank Income Classification, WBIC). Their environmental policy trajectories in the second half of the XX c., reflect the legacies of the experiences of 'late incorporation' of great expanses of 'nature', construed as 'empty' by the colonizing settlers carrying 'modern' (western, capitalist) society. These experiences can be understood as equivalent because both reflect the incorporation of landscapes identified as 'rich' in natural resources, and 'open'. This is, despite the presence of original peoples and their roles managing and transforming those environments. The convergence is exacerbated by the large size and relatively peripheral (distant and isolated) position of these territories, and by their position and connection to the, then core, of the World Empire, the United Kingdom during the late XVIII c., up to the Statute of Westminster in 1931.

This brief example of highly supported (AU > 0.99) binational clusters, suggests how clustering provides informative criteria to select cases to advance the comparative study of the dynamics of environmental policy as revealed by the components of the NFA.

In this paper, I will discuss the main branches of the dendrogram of the cluster analysis, or 'tree'. These are the first branches starting from the root of the tree up to the inclusion of a major division among the countries of the world that emerges from my analysis, the international rift (following section). These branches include clusters, all of which have AU higher than 0.90, and single-country branches (frequently designated with the oxymoron single-entity clusters).

3.2.2 A world divided into two, the international rift

The international rift is due to the bimodal distribution of the variable slope (θ), which grants the differentiation of the dataset into two major groups (Figure 2). The title of this section references the notion of the metabolic rift, first identified by Karl Marx and recently expanded by Foster *et al.* [203].

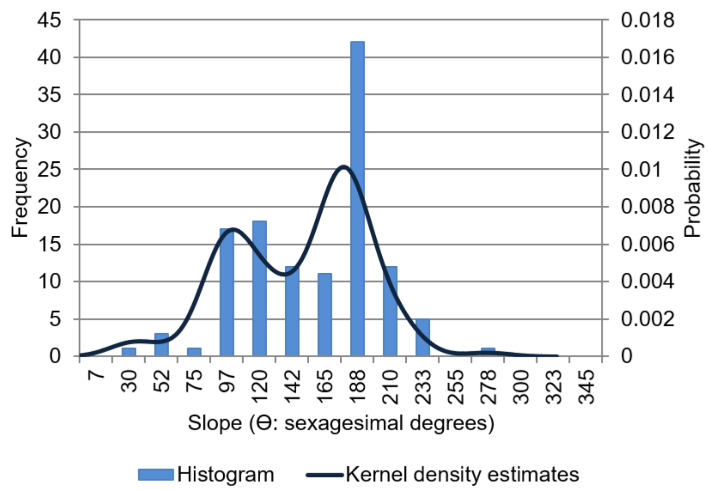


Figure 2 Histogram of the slope (Θ) of the simplified NFA trajectories
Kernel density estimates show the distribution is bimodal.

There are two major groups and a few (n = 4) countries in the margins of the distribution. On the one hand, NBTO (n= 71, Θ within 141.0° and 222.4°), are countries where decreases of BCP from one year to the next, are larger than changes in EFP (increases or decreases). On the second hand, PBTO (n = 48, Θ within 45.0° and 135.1°), are countries where increases in EFP, are larger than changes in BCP (increases or decreases). The countries in the margins of the distribution of slope are Hungary (Θ = 29.6°), Bulgaria (31.1°), and Romania (31.6°), for which, increases in BCP are higher than increases in EFP, and the U.K. (277.8°), where the decrease in EFP is much higher than the increase in BCP.

The distribution of the slope variable also leaves an empty space of 111.8° between 277.8° and 29.6° which means that there are no countries making gains in BCP while decreasing near equivalent amounts of EFP in the dataset. This range would correspond to the hypothetical situation of ecological 'recovery' simultaneous with a slow-passed societal collapse, or to an extraordinary, but apparently improbable, sustainability revolution. A simultaneous, and therefore, necessarily coordinated decrease in EFP and an increase in BCP.

Notably, the two major groups identified are conceptual opposites (not geometric opposites). Meaning, NBTO are countries 'losing' biologically based production (BCP) without proportional increases in ecological consumption (EFP), while PBTO are countries notably increasing ecological consumption, without concordant changes in biologically-based production, neither proportionally increasing production nor 'apparently' losing productive capacity from one year to the next.

3.2.3 Clustering dendrogram

The resulting tree of my analysis is asymmetrical. That is, the tree includes several branches with few or a single country, and another branch clustering all the remaining countries (n = 98 to 122). This structure occurs because three of the four variables used for clustering exhibit nearly exponential distributions (BC_f, EF_f, and Tl), and at least two of them (BC_f and EF_f), are not strictly associated. This structure is a common occurrence with single linkage clustering, where it is referred to as “chaining”, and historically has been deemed undesirable and has been avoided or explained away. The frequency of this structure in single linkage clustering may be due to the frequency of nearly exponential distributions in ‘natural’ datasets (Power functions, Pareto, etc.). This structure merely tells us that there are a few small clusters and entities (countries in the present case), which exhibit comparably unique characteristics relative to most of the other entities in the analysis.

Figure 3 shows the dendrogram that I will discuss in this paper. There are fifteen major clusters (C1 – C15). Six are single-country branches, six are small clusters (2 - 5 countries), and three are large clusters (10, 40, and 48 countries each). In Figure 3, I ordered the clusters left to right following the order of the tree (from more distant entities to less distant entities). This order kept most NBTO countries to the left. To emphasize this distinction, I moved C13, Luxembourg (C14) and, the U.K. (C15) to the right, this order made it that most European countries ended on the right of the dendrogram (with the exception of Albania and the Scandinavian countries, which are all NBTO, Denmark is PBTO and is found in C12 to the right of the figure).

Consequently, Luxemburg is the only NBTO country to the right of the dendrogram, an exception that is easy to justify. First, Luxembourg is closest to most other European countries, especially, other high EFP countries. Second, Luxembourg's NBTO trajectory seems to be a secondary effect of this country having the highest EFP in the dataset, both in 1961 and in 2014. Appendix 5 provides detailed tables for the taxonomy.

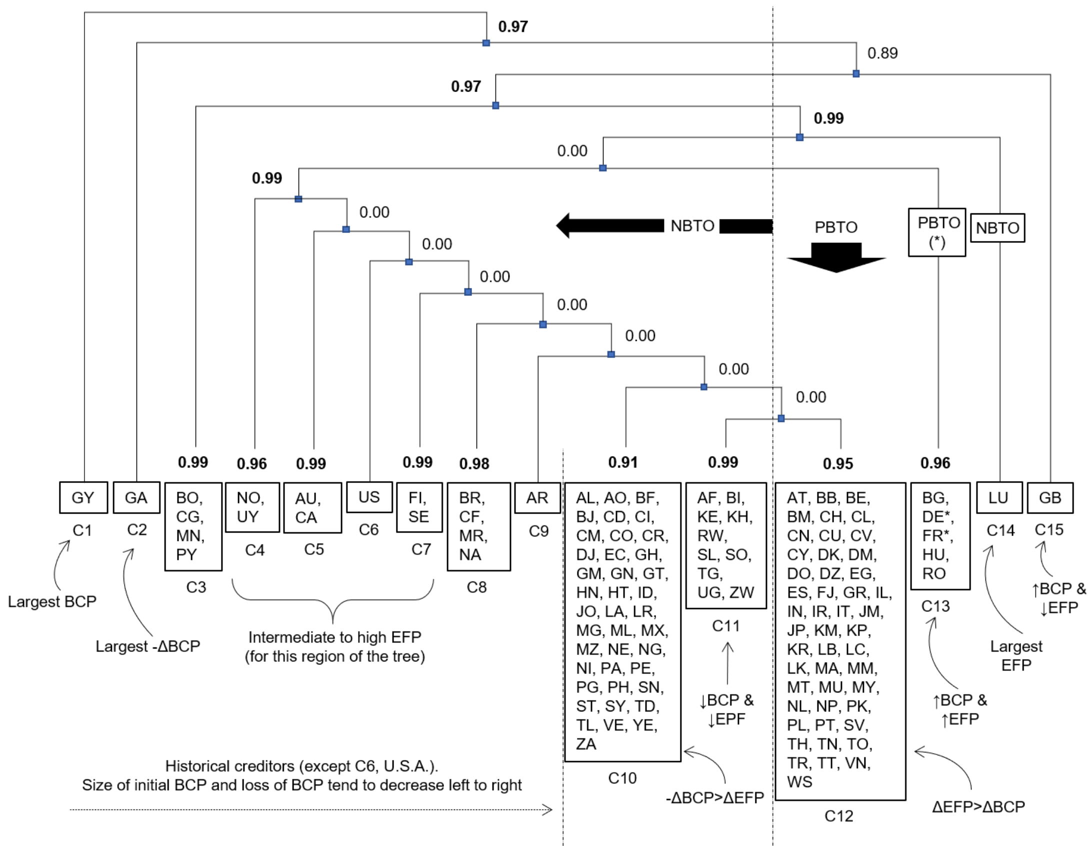


Figure 3 Dendrogram of the cluster analysis
Countries are identified by the International Organization of Standardization –ISO two-letter codes [2], included in Appendix 5. Approximately unbiased probability estimates (AU) of each node are presented [105,106,198]. **Bold** AU > 0.90. NBTO: Negative Balance Trade-Off; PBTO: Positive Balance Trade-Off. Annotations are presented as mnemonic devices, see the full text for a detailed description.

3.2.4 NFA taxonomy overview

C1 to C10 have NBTO trajectories (slope, θ: 141.0° to 222.0°). C1 to C9 are all historical creditors except for C6 (U.S.A.), which is a historical debtor. C4, C5, C7, and C9 (Argentina) correspond to what Niccolucci *et al.* [168] termed "parallel". Here, they do not correspond to one cohesive group, but to four different clusters. The criteria used by [168] to characterize it, that: "BC[P] and EF[P] trends proceed in 'parallel,' with slow or small changes over time", is incorrect; because, some of these countries exhibit high decreases of BCP (C5), while others exhibit the highest decreases of EFP (C4). The unifying characteristic of these clusters, otherwise, historical creditors with high BCP and high BCP losses, is that they also have intermediate to high EFP. This is, in comparison to C1 (Guyana), C2 (Gabon), C3, C8, and part of C10, i.e.: "wedge", the group that they are contrasted to in [168].

C11 and C14 (Luxembourg) also have NBTO trajectories (θ: 189.5° to 222.4°), with slopes overlapping with C1-C10. Nevertheless, here, decreases of BCP always associate with decreases of EFP, and with extremely high EFP (C14), or with very low BCP and EFP (C11). This situation was termed "descent" by [168], however, here it is represented by two significantly different clusters.

C12 and C13 include all PBTO countries (θ: 29.6° to 150.3°). All change in BCP is negative in C12, and positive, but small, in C13. C12 and C13 include seventeen out of twenty-three European countries, the other six European countries are found in single-country branches C14 (Luxembourg) and C15 (U.K.), in small, binational clusters C4 (Norway) and C7 (Finland and Sweden), and in C10 (Albania).

The small overlap between the NBTO and PBTO slopes (5.3°) is explained by only one country (Chile), clustered in C12 with AU lower than 0.99 but, nevertheless, higher than 0.95. Other variables besides slope help separate these clusters.

C15 (U.K.) constitutes a single-country branch. It is the only country, simultaneously, gaining BCP (also small), and losing EFP. Its loss of EFP unfolds from a high initial value (6.15) in 1961.

Figure 4 illustrates the results of this research. Note the contrast in orientation between green, orange, and red trajectories, mostly horizontal or descending (NBTO), and purple and blue trajectories, mostly vertical (PBTO).

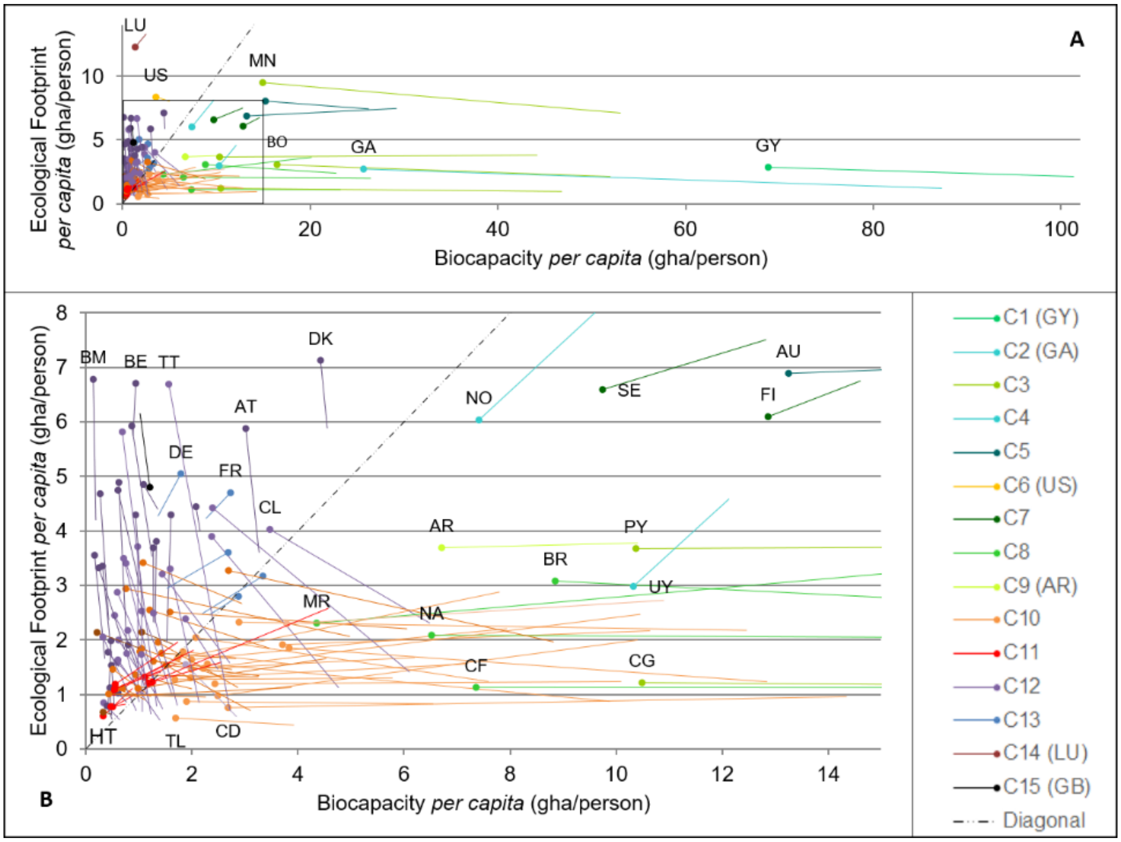


Figure 4 An international sustainability classification
A: overview plot; **B**: enlarged area. The diagonal in the plots (dash-dot-dot line) marks the ecological self-sufficiency frontier (EF = BC), ecological debtors (EF>BC) are found to the left, and ecological creditors (BC>EF) to the right. Colors correspond to clustering dendrogram branches, see Figure 3 for the detailed composition. ISO two-letter codes are included for some countries as a reference.

Figure 4 also shows that clusters C1 (Guyana), C2 (Gabon), C3 (without Mongolia), C8, C9 (Argentina), C10, and C11, all low to intermediate EFP, follow trajectories that 'could be' sequential. This leads to a corresponding sequence in sustainability labels where historical debtors are first to the left (C11), followed by recent debtors (C10) and then historical creditors (C1 – C9). This apparent ordering suggests that the corresponding countries have followed a similar process, i.e.: environmental and consumption policies, but from different starting points, at different paces, or starting at different moments (in waves). Similar sequences can be identified within C12 going from bottom to top (from historical creditors to historical debtors), between C12 and Germany and France (in C13), and less reliably among the high EFP, historical creditors C5 (Australia and Canada), C7 (Finland and Sweden) and Norway (from C4). Appendix 6 provides a description of each of the main branches (C1 – C15).

3.2.5 Contribution of each variable to clustering

The consistency and discriminating power of the variable slope are notable. In six of the eight clusters comprising two or more countries (three-quarters), the slope is homogeneous consisting exclusively of NBTO countries. In C12, the largest cluster in the results, PBTO countries are dominant (46 out of 48, 96%); Chile and Malaysia are the exceptions with NBTO slopes, which are, nevertheless, the third and the first closest to the boundary between the two groups, i.e.: with cluster C10, all of which is NBTO. Finally, C13 is formed by five European countries, two PBTO countries (France and Germany), the first and second countries found from the lower end of the distribution of slope within PBTO, and by the three countries to the lower margin of the distribution of the same variable (Hungary, Bulgaria, and Romania).

Furthermore, out of 105 inter-branch comparisons, there are twenty-four overlaps involving the variable slope (23%), making it the second most useful for distinguishing clusters. It is worth remembering that consistency and discriminating power are not strict requirements for the variables in a cluster analysis, nevertheless, these characteristics validate the incorporation of the variable in the analysis and call attention to its interpretation given its importance to distinguish and characterize branches.

Modern human populations, fraction and, consequently, reduce BCP when we encounter it, and, in proportion to its abundance. The second major pattern explaining the clustering is the exponential distribution of BCP and of losses of BCP (which explain most of the overall change of most countries throughout the study period, i.e.: Tl). The countries in the dataset are distributed along a gradient from great losses to small gains of BCP. When looking at inter-branch comparisons, there are only eighteen overlaps involving this variable (17% out of 105), making it the most useful for distinguishing branches. Most of the decreases of BCP, but not all, maybe explained by population growth [177]. Lastly, the correlation between BCP at the beginning of the study period and its change over the study period is the highest correlation among the variables considered in this study (non-linear correlation rho = -0.93).

Concluding, 73.2% of the countries show increasing EFP (n = 90), for the most part, this was to be expected. What is notable is that 26.8% (n = 33) of the countries show diminishing EFP. The larger than expected number of countries losing EFP calls attention to these countries, as in most cases, it is not occurring at the level nor in countries where a reduction of EFP may be explained as a consequence of 'efficiency-improvements'. Twenty-one of these countries, exhibit EFP lower than the world's available BCP ($\bar{Y}$ = 1.15, SD = 0.28, World's available BCP = 1.68). This result is not consistent with the predominant narrative in the field of development. It is consistent with the critique enunciated in the introduction, and illustrated by the work of Vaggi [140].

The ongoing stratification of nations in terms of EFP is suggested by the distribution of the direction of change of this variable. Table 3 shows the distribution of countries decreasing and increasing EFP, relative to ranges defined by 'natural' brakes. Table 3 shows higher percentages of countries are decreasing EFP at high and low levels. This observation suggests that countries are aggregating around specific levels. At the same time, a higher percentage of decreases occur within the lower range. These results persist if we use three balanced ranges (41 countries each) and if we use only two ranges as defined by the median (below and above).

Table 3 Distribution of the direction of change of the EFP (1961-2014)

EFP (gha/person, 2014)	Decreasing	Increasing	Percentage decreasing	Total countries within range
> 5.8 - 12.3	5	10	33%	15
5.0 - 1.5	11	66	14%	77
< 1.3 - 0.57	16	15	52%	31
			Total	123

Notice EFP ranges are defined by large gaps.

Social-ecological ‘decline’ and maybe even ‘collapse’ –understood as the loss of conditions to generate ecological-production-surpluses, to increase biological productivity, to increase low EFP, and, probably, to support the increase of local population– may be occurring at the level of nations or sub-national regions. The present study identifies a group of countries that seem susceptible to social-ecological decline and collapse (C11), all are NBTO countries.

The frequent overlap among clusters when using the variable EFP, suggests there are multiple paths to ‘development’. There are forty overlaps involving this variable when doing inter-branch comparisons (38%), making this variable the least useful for distinguishing branches. Using EFP as a proxy for ‘development’, in a similar manner as income metrics *per capita* have been used historically, I observe that very high EFP countries belong to a great diversity of branches and span a great range of BCP (range = 15.11).

Fifteen countries from seven different clusters have very high EFP (> 5.8). Most of these countries cannot be grouped together easily, except for the fact that they have very high EFP. From this point of view, there is not such a category as 'developed', and therefore, there is no one path for the rest of the countries to follow. A similar diversity of clusters and ranges of BCP, is also found in the nations with high intermediate EFP (min BCP = 0.16, max_1 BCP = 68.80, max_2 BCP = 25.69, $range_1$ = 68.64, $range_2$ = 25.53, ten clusters), and low intermediate EFP (min BCP = 0.43, max BCP = 10.49, range = 10.06, five clusters). Therefore, classifying countries based exclusively on EFP or a highly correlated proxy (like income *per capita*) alone seems to be misleading at every level. The high intermediate range of BCP, just enunciated, includes the extraordinarily high values of Guyana, i.e.: max_1, and Gabon, i.e.: max_2, the pattern persists even if we move on to the third-highest value in the category.

3.3 Contrasting environmental trajectory (clustering), sustainability labels, and Income

When comparing the World Bank's 2014 Income Classification – WBIC [194] to my results, I observe that higher-income countries tend to be debtors, they exhibit PBTO, and most of them are found in C12. Twenty-two out of thirty-three High-Income countries (HIC) are historical debtors

(66.7%), four more are recent debtors, and nineteen of them are clustered in C12. Furthermore, sixteen out of thirty-three Upper-Middle-Income countries (UMIC) are also clustered in C12 (48%), three of these are historical debtors and thirteen are recent debtors.

Alternatively, countries with lower income are concentrated in major NBTO clusters (C10 and C11), and they tend to be historical creditors or only recent debtors. The highest number of Low-Income countries (LIC) is found in the historical creditors lumped in C10 (n=6). Overall, thirty-nine out of fifty-seven (68%) Low and Lower-Middle-Income countries (LMIC) are found in C10 (n=29) and C11 (n=10); fourteen of these are historical creditors, ten are recent debtors, and only five are historical debtors. Only ten out of thirty-three Upper-Middle-Income countries are found in C10 (30%), and none are found in C11.

In addition, recent debtors are evenly distributed among major PBTO and NBTO clusters, nevertheless, income distribution follows the tendency that has already been described (higher income associated with C12 and lower income associated with C10 and C11). Twenty-four of these countries are found in clusters C10 and C11 (19 and 5 respectively) and Twenty-three are found in C12.

Most remaining countries are historical creditors (n=17) and found in clusters C1 to C9. These are distributed among the WBIC with a slight bias toward higher-income categories (LIC=1, LMIC=4, UMIC=5, and HIC=7).

Finally, the U.S., the U.K., and Luxembourg are single-country branches, High-Income, and historical debtors. The U.S. stands out for being a historical debtor among single-country and small, NBTO branches, with varying levels of income and EFP. Meanwhile, the U.K. and Luxembourg, although with unique trajectories, seem less odd when it is realized that neighboring clusters C12 and C13 contain seventeen (out of 23, 73%) European countries, out of which fifteen are also High-Income. And, that twenty (87%) European countries were already debtors at the beginning of the study period. Finland, Sweden, and Norway, all, Scandinavian countries, are the only historical creditors from Europe. Figure 5 shows the distribution of countries by branch, sustainability label, and the 2014 WBIC [194].

	Historical Creditor				Recent Debtor				Historical Debtor				Recent Creditor				
WBIC	LIC	LMIC	UMIC	HIC	LIC	LMIC	UMIC	HIC	LIC	LMIC	UMIC	HIC	LIC	LMIC	UMIC	HIC	Row total
C1 (GY)		1															1
C2 (GA)			1														1
C3		2	2														4
C4				2													2
C5				2													2
C6 (US)												1					1
C7				2													2
C8	1	1	2														4
C9 (AR)				1													1
C10	6	7	5		5	10	3	1	1		2						40
C11	1				4	1			4								10
C12		1			2	5	13	3	1	4	3	16					48
C13												3			2		5
C14 (LU)												1					1
C15 (GB)												1					1
Column total	8	12	10	7	11	16	16	4	6	4	5	22			2		123
Sustainability label total	37				47				37				2				123

Figure 5 Contrasting sustainability and Income (WBIC)
Contingency table showing the number of countries by branch (rows), sustainability label (major columns), and the World Bank 2014 Income Classification [194] (minor columns). WBIC: World Bank Income Classification, LIC: Low-Income Countries (purple), LMIC: Lower-Middle-Income Countries (blue), UMIC: Upper-Middle-Income Countries (green), H: High-Income Countries (orange). The intensity of color reflects the number of countries relative to each income category. Branches: C1 – C15 (ISO two letters codes are included for single-country branches). Sustainability label (see table 1).

Another notable pattern is found in Figure 5. Low-Income countries are found in four branches, Lower-Middle-Income countries and Upper-Middle-Income countries are both found in six branches, and High-Income countries are found in ten branches. This pattern remains if only single-country branches are considered (LIC=0, LMIC=1, UMIC=1, and HIC=4). This pattern suggests that the distinctiveness of environmental outcomes increases with income. This may be because countries with higher economic capacity have better conditions for determining their environmental policies. Or, moving in the opposite direction, because more powerful countries that can command singular environmental policies also achieve higher levels of economic activity. In any case, lower income associates with less distinctiveness of environmental outcomes, and with being either a historical creditor or (more frequently) a recent debtor.

The results reported in this section offer interesting challenges for the advancement of World-System theories of development [204–215]. If wealthy/powerful countries followed distinctive 'development' paths and demonstrably different environmental and consumption policies, how do they become part of a coordinated/shared structure? i.e.: how do transnational institutions relate to the increase of national ecological consumption? and, if there are multiple 'cores', are there multiple (overlapping?) peripheries? and how are conflicts about peripheries mediated among those cores? An additional comment regarding core-periphery (and semi-periphery) theories will be made in section 3.5.

3.4 Geographic distribution

Figure 6 shows the geographic distribution of branches and sustainability labels. It shows C12 corresponds mostly to Europe, continental Asia, most of the islands in the dataset (seventeen out of twenty), and countries in the north of Africa, with El Salvador and Chile as the only countries from continental America. Therefore, this cluster is found mostly in the 'old world', in areas with a long history of 'civilized' occupation (high densities, agriculture, trans-boundary trade, etc.), and in environmentally challenging areas (low natural BCP, islands, and sub-xerophytic and xerophytic areas). The challenging geometries of El Salvador and Chile may have played a role in their belonging in this cluster. Nevertheless, a reference to the possible role of political change toward liberalism forced through military intervention, in these 'new world' countries seems also unavoidable [216,217].

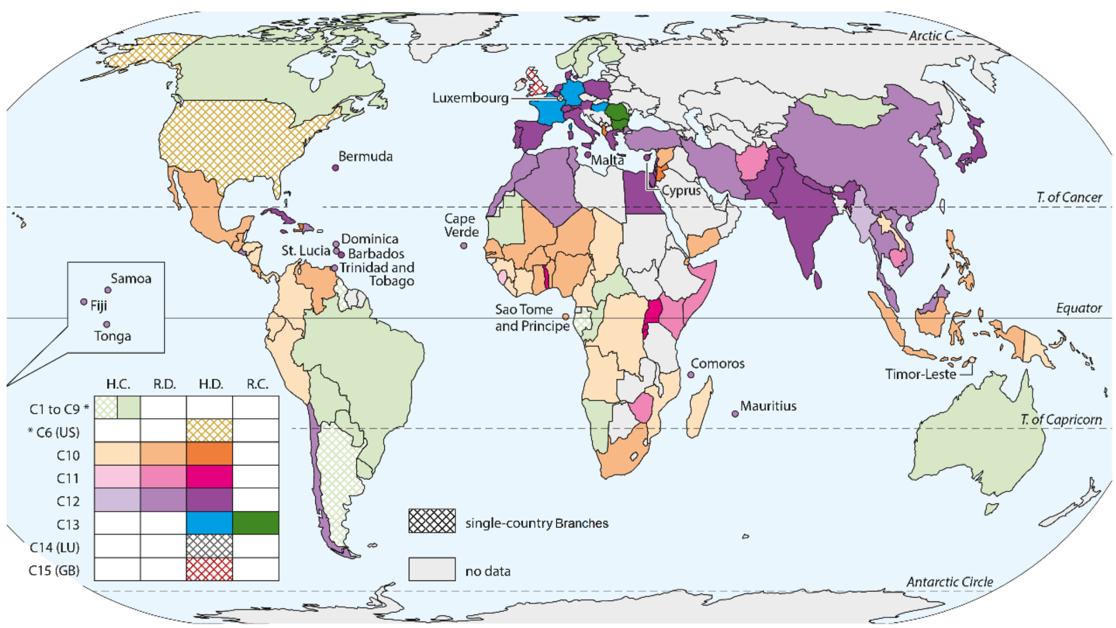


Figure 6 NFA 'regions' of the world (1961 – 2014)
Countries are colored according to the legend by branch and by sustainability label: H.C.: Historical Creditor, R.D.: Recent Debtor, H.D.: Historical Debtor and, R.C.: Recent Creditor. *: C1 to C9 excluding C6 (historical creditors with high or very high BCP and varying decreases of it

are joined by the same convention), C6 (U.S.A., NBTO, a historical debtor with high EFP is represented with a unique convention).

Historical creditor countries (C1 to C9) are found in Scandinavia, Mongolia, Africa, and in the 'new world', in Australia, Canada, and South America, and many of these countries have relatively large territories. C10 is found mostly in the 'Global South': in Central and South America, Africa and part of South East Asia (Laos, Philippines, Indonesia, and Timor-Leste), with Haiti, Timor-Leste and the archipelago of Sao Tome and Principe as the only island systems in this group. C11 is found in Africa, especially East Africa, and in Central (Afghanistan) and South East Asia (Cambodia). A reference to the role of military intervention and its 'justification', as a shared, underlying cause for the observed outcomes of environmental policy also asserts itself in the case of C11 [218].

The cartography of the international sustainability classification shows that continents do not provide good criteria to group the information of the NFA. Also, that broad political-economic categories like 'global south'/'global north' must be problematized. A distinction between 'Old' and 'New worlds' seems to be equally important and, nevertheless, incomplete. Instead, multiple aspects of physical geography (biological productivity e.g.: climate and hydric balance, land area, and sea access), and human geography (history of occupation, population density, and historical contingency) interact to produce a particular world map. This map requires us to make previous political-economic, sociological, and international relations categories more precise.

3.5 Synthesis

The fact that a large number of countries are increasing their EFP yearly, beyond their BCP implies that the excess resources that they are consuming were obtained abroad. The fact that a large number of countries is also decreasing BCP yearly while their EFP decreases or remains virtually unchanged, suggests that part of the natural capital that supports their BCP may be being reduced by exports abroad (this may be the case even if population growth and other factors are equally or more important). The fact that these two groups are to a very large extent mutually exclusive, and the contrasting social-economic (EFP and income) and environmental (BCP) outcomes, strongly supports the notions of unequal exchange and unequal ecological exchange (see also dependency/core-periphery and 'green' world systems theories, [219–223]).

This configuration suggests the ongoing exploitation of a large set of nations by another by means of extractivism [224–229]. A 'mode of production' oriented toward 'development', understood as state-led economic growth based on natural resource exports.

For academic observers and activists, extractivism implies the depletion of the resource base along with conflicts caused by negative social and ecological impacts of intervention and extraction. Extractivism today goes beyond mining and fossil fuel extraction does not have to be formally coordinated, can also affect 'internal-peripheries', and can involve self-exploitation. The persistence of these processes for at least half a century forcefully implies the existence and continuous deepening of ecological debts [169,230–235].

The notion of a semi-periphery is more difficult to define and recognize from the results of this study, mainly because changes in direction (oscillating up and down) were irrelevant in my statistical analysis. Nevertheless, the distinction between historical and recent (creditors and debtors) helps recognize multiple 'development' paths regarding timing, echoing the notion of 'late development' and forcing us to recognize the corresponding possibility of concurrent 'late under-development'. In other words, the fact that the nations from different clusters follow similar trajectories but, from (or at) different positions, which may be interpreted as sequential (one following the other), suggests that some clusters may be differentiated as following the 'same' trajectory (policy) at different historical moments. Nevertheless, the uneven attainment in socio-economic outcomes observed within major clusters may correspond to an additional instance of stratification. The world is simultaneously divided into underdeveloping countries, core-periphery, and stratified into different levels of ecological consumption (and income *per capita*).

3.6 Critical assessment

For the following assessment, first, I address the critiques that have been raised about existing development taxonomies, and that I reviewed in the introduction. Second, I elaborate on the issues that offer opportunities for improvement based on the experience of my own proposal.

3.6.1 Addressing criticism of existing development taxonomies

My hope is that by pursuing peer-reviewed publication I may accomplish more clarity than it has been granted to the development taxonomies critiqued [138,141]. Furthermore, the peer-review process opens up work to inspection for obscure political biases [135,136,139], and, in any case, this more public process can serve as an extension of the 'public sphere' for citizens to engage in the necessary political dialogue regarding the issues that concern them as, among many others, sustainability.

My proposal to formulate an international sustainability classification is informed by theories of clustering and of classification, especially regarding the distinction that cluster analysis is a numerical technique for classification, while classification is a purpose-oriented, social, cultural and political process which must be judged by its usefulness in a specific context [112,113,236]. This proposal is also informed by theories of indicators, sustainability, and by the work behind footprinting in general, and the NFA in particular. Consequentially, this work is unavoidably informed by theories of thermodynamics, systems science, and ecology [237]. Furthermore, contemporary analysis of NFA and the Ecological Footprint has established itself comfortably within Environmental Sociology, and I hope, I have conveyed the sense that theoretical contributions from Economics and Political science (and policy practice) are most desirable to inform further development of this and other development taxonomies.

The issue of non-linearity of ‘development’, i.e.: that more of a variable (usually income) simply does not translate into better human-social progress and wellbeing, has been addressed in my proposal three ways. First, by using two complementary dimensions. As it can be observed in the results, countries that move in four different directions can be identified (simultaneously increasing or decreasing both BCP and EFP or, alternatively increasing or decreasing one or the other). This allows us to see that countries found at a similar level in one variable may nevertheless follow opposite trajectories, with implications for our understanding of their past and future sustainability. Second, the method for classification proposed is dynamic [139]. This means that the classification can be iterated for other time periods, and it can be iterated for shorter or longer time intervals. This characteristic invites historical analysis and allows for the study of the complexities of the time scale. Third, even though, merely illustrated in my analysis, the classification provides an opportunity to explore complex issues which may generate non-linear behavior like the role of geopolitical power in mediating the relationship between national income and the access to biologically based production in the international arena, or the ability to protect or not, the biological assets that support domestic production.

Finally, in the case of thresholds, one strength of cluster analysis as performed in the present study is that thresholds are defined objectively for a dataset. The results can be reproduced by replicating the statistical analysis. Uncertainty can be incorporated, as I did, to define the levels for the analysis and to assess their validity. Cluster analysis provides clear thresholds that differentiate branches along multiple variables simultaneously. This helps explain the differentiation of entities that may seem similar regarding only one variable. Finally, thresholds in cluster analysis are not single value boundaries but ranges that extend between the maximum in one branch and the minimum in the next (or vice versa), and where these distances (dissimilarities) between branches tend to be higher than distances among member within each branch.

3.6.2 Opportunities for future improvement

Despite its virtues, certain aspects of my proposal remain arbitrary and seem susceptible to further improvement. First, using line-segments as a simplified description of the trajectories of BC and EFP was a very successful and robust strategy to deal with "the high dimensionality, very high feature correlation, and typically large amount of noise that characterize time-series data", which were described by Aghabozorgi *et al.* [190] as "barriers that fail most of conventional [sic] clustering algorithms to work well for time-series". Nevertheless, in the future, it is desirable to use more detailed descriptions of the time-series, for transparency, and to explore the variations in direction and rate within the trajectories. To achieve this, it is possible to explore multiple alternative approaches to time-series clustering [189,190,238]. However, it is also necessary to develop clear explanations of the working of the algorithms and of the results, including methods to assess the uncertainty in these more complex methodologies.

Second, standardization of the variables before clustering is a thorny issue that is still open to debate and requires further investigation. The simplicity of the description used in this study minimizes its effect.

Nevertheless, most available advice is in favor of standardizing all variables independently and technical development focuses on identifying the adequate method for standardization. This is despite Milligan's [111] assertion that: "Unfortunately, many researchers fail to recognize that if clusters actually exist in the original variable space, then standardization, can distort or hide the clustering present in the data". In the present example, three variables have the same units (EF_f, BC_f, and Tl) and correspond to measurements of the same 'things', nevertheless, two of these variables correspond to opposite ends of the same process (EF_f, and BC_f) and the third variable (Tl) is a derivative. This raises the question of whether they should be treated as independent measurements or as equivalent measurements of the same process. Lastly, the slope measurement (θ) is scale-invariant. That is, the angle of the trajectory is the same independently of the scale of the representation of all the other variables. How should this variable compare to the others? [109] found '0-1 scaling', consistently, in the superior performance group across clustering methods, notwithstanding, there is no particular reason why the range of different variables should all be made equal to one. The effect of alternative scaling rules should be assessed, and more importantly, we need to understand their implications for the interpretation of results.

Third, is the issue of method selection in clustering. Regarding this issue, in closing their chapter on hierarchical clustering Everitt *et al.* [112] concluded:

> "The main problem in practice is that no particular clustering method can be recommended, since methods with favourable mathematical properties (such as single linkage) often do not seem to produce interpretable results empirically. Furthermore, to use the results involves choosing the partition, and the best way of doing this is unclear".

In addition, single linkage has been found to "produce unbalanced and straggly clusters ('chaining'), especially in large data sets" [112], and other scholars in the field of development taxonomies have preferred Ward's method because it "has been proven to be especially suitable for *building clusters with similar sizes*, *when no outliers are present*" [146] (emphasis added). I contend that the simplest, most straight forward method of classical hierarchical clustering using single linkage and Euclidean distances with "optimal theoretical properties" offers a transparent representation of the structure of datasets. And, that it is necessary to learn to 'read' these representations to understand the world "unbalanced and straggly", as it is. Furthermore, development datasets are laden with exponential differences that introduce the effects of outliers in the analysis (as all 'natural' datasets are), requiring addressing the issues of transformation and standardization enunciated in the previous paragraph, instead of censoring data by the simplistic procedure of labeling them 'outliers'. Otherwise, the argument for an *a priori* preference regarding the shape of clusters remains unjustified, as are obscure methods, with weak or unknown theoretical properties that produce more palatable results.

Finally, I found that recent developments in multiscale assessment also facilitated interpretation by avoiding the choice of a partition [105,106], a practice that also involved arbitrary decisions (all clusters had to be defined by the same distance). Supportively, in the latest edition of the most authoritative textbook on the subject, Borcard *et al.* [199] acknowledged the developments of multiscale bootstrap resampling, as an "enhancement" to the "choice approach", "to assess the uncertainty (or its counterpart the robustness) of a classification". Accordingly, I suggest that these developments contribute to the advancement of the issue of method selection by pursuing transparency over preference.

4 Conclusions

In the present study, I demonstrated a data representation that allows us to compare multiple nations simultaneously in terms of the components of the NFA, EFP, and BCP. The ecological balance of EFP to BCP is a measure of a nation's ecological self-sufficiency, a useful metric to assess its contribution to planetary sustainability.

I tested statistically the trends of these NFA components and found that: neither technological nor social-political or other events have, so far, effectively changed the direction of the trends in BCP and EFP of all tested nations between 1961 and 2014, making the period broadly homogeneous from this point of view. Minor changes in direction and changes in rates were not evaluated in this study.

In addition, attending to critiques of existing development classifications, I demonstrated a transparent and simple clustering procedure, grounded in theory both regarding the content of the analysis and technical execution, and I applied the most advanced techniques available to assess the robustness of the results.

Most countries (119 out of 123, 96.8%), can be identified as either PBTO, i.e.: countries where increases (gains) in EFP, are larger than changes in BCP (increases or decreases), or, NBTO, countries where decreases (loses) of BCP from one year to the next, are larger than changes in EFP (increases or decreases). Furthermore, PBTO countries have been ecological debtors (EFP>BCP) for most of the study period (twenty-six historical debtors and twenty recent debtors out of 47 countries, 98%), they tend to be wealthier in terms of income *per capita* (section 3.3), and include South Korea, Japan, and most western continental Europe (excluding the

Scandinavian peninsula). At the same time, NBTO countries have been ecological creditors (BCP>EFP) for most of the study period (thirty-nine historical creditors and twenty-seven recent debtors out of 72 countries, 91.7%), they tend to have lower income *per capita* and are located more frequently in the 'global south', Central and South America, Africa, and Southeast Asia.

In general, this configuration strongly lends support to notions of unequal exchange and unequal ecological exchange (see also dependency/core-periphery and 'green' world systems theories). This is, this configuration suggests the ongoing exploitation of a large set of nations by another by means of extractivism. There is no implication for the coordination among PBTO countries in these processes, for the role played by NBTO countries (active or passive), and for the awareness (consciousness) of citizens in these processes, none of these conditions was investigated nor could have been investigated in this study. Notwithstanding, the persistence of these processes for at least half a century forcefully implies the existence and continuous deepening of ecological debts.

The divide between PBTO and NBTO countries generally follows similar distinctions between core/global north, and periphery/global south nations. Nevertheless, the methodology demonstrated offers a starting point for a more precise description of the historical process.

The results of the cluster analysis offer more details identifying fifteen main branches, where slightly less than a quarter of the countries (27, 22%), distributed in twelve clusters show some variation on the general pattern just described. These variations involve, i) six NBTO countries with intermediate to high Ecological Footprints (C5, C7, Norway and Mongolia), ii) eleven NBTO countries with relatively large BCP and corresponding large losses of BCP (all intermediate to low EF), iii) the U.K. (i.e.: C15, the only country decreasing EFP, from a former high level and increasing BCP), iv) two PBTO and three closely related European countries slightly but continuously increasing BCP (C13), v) Luxemburg (i.e.: C14, the country with the highest EFP in 1961 and 2014), and vi) the U.S. (C6), the only large, NBTO, 'new world' country that is a historical debtor. The most important interpretation of these variations is that there has been variation in the start and rate of the process of ecological exploitation and in achieving higher ecological consumption (high EFP). This is, that the processes identified with the cluster analysis may have occurred in waves, at least for some countries. There is support for this observation also inside major clusters (C10 and C12).

Despite major contrasts and variations, most modern countries are fractioning and reducing BCP in proportion to its abundance (117, 95.1%). Distribution in BCP decreases (losses), is the most useful variable to distinguish clusters followed by the variable slope which underlies the PBTO/NBTO distinction.

The distribution of the EFP and the change in EFP, are less useful to distinguish clusters. This reflects the fact that changes in EFP overlap more frequently, because of ongoing stratification. In the extremes of this distribution, we can see the contradiction of some very-high EFP countries consuming, even more, every year and, many low and very-low EFP countries consuming ever less, down to seemingly dangerous levels. The cluster analysis identifies a group of ten countries that seem vulnerable to an ecological decline (C11). Notably, the conditions of C11 may be predictive of the conditions of many more countries in C10 (n=40).

Even though there were no significant changes in the direction of the trends studied in this research, it will be valuable to study the variation in the rates of change of BCP and EFP to learn more about how these trends have changed over time. Also, a study of the trajectories of (national) EF and BC, country by country and year by year, is necessary to complement the present work.

Finally, the execution of the present study stands as a demonstration that the goals of human and social progress can be helped by the broad involvement of citizens in the study and understanding of issues relevant to them, like sustainability. A scientific understanding of the trajectories of BCP and EFP (and BC and EF) can be advanced by the public availability of the data and tools used in the present analysis, and by participation in the peer-review process. The international sustainability classification presented in this study offers an opening to engage with social issues like widening (or narrowing) differences among nations, environmental/ecological (in)efficiency, unequal exchange, unequal ecological exchange, and ecological debts.

CHAPTER 3 TECHNICAL NOTE: ADVERSE IMPLICATIONS OF THE IMPLEMENTATION OF A 'SLOPE' VARIABLE EXPRESSED IN SEXAGESIMAL DEGREES, FOR THE SIMULTANEOUS REPRESENTATION OF TWO 'COMPLEMENTARY' TIME SERIES

Context of the problem

In the paper included in chapter 2, I proposed a simplified description of the joint trajectories of the two time-series composing the NFA of each country. "This simplified description corresponds to a line-segment defined in a two–dimensions orthogonal coordinate system (an XY-plot)", using four variables (chapter 2, section 2.3):

> "The EFP and BCP coordinates at the end of the period of analysis (EF_f and BC_f), the length of the segment or trend length (Tl), computed using Pythagoras' theorem; and, the slope of the segment (θ), expressed in sexagesimal degrees, obtained by computing the arctangent of the slope of the segments expressed in term of the Cartesian coordinates."

I further stated that:

> "The present analysis can be understood as an application of features-based time-series cluster analysis [189,190], where each country is modeled using one linear equation (*not a function*) to represent two time-series simultaneously, and features are extracted from the resulting model" (highlight added).

The distinction regarding functions is important because linear functions are standardly described using an intercept in the vertical axis and a slope defined as $m = \Delta y/\Delta x$.

I did not use functions because the features obtained from this description (function parameters) would have been inappropriate as inputs to the cluster analysis. On the one hand, the intercept of the linear function is not meaningful for the description of the NFA trajectories as it is not even part of the trajectory. NFA trajectories cannot reach zero, 'by definition', if there is no-consumption, there cannot be people, i.e.: no nation/territory is defined this way [156]. On the other hand, the slope of the linear function is not and equal-interval variable.

Attending to the theory of cluster analysis [109,111–113,236], it was important to me that the features describing my models were necessary, sufficient, and meaningful, and that they were continuous, equal-interval variables (that they varied continuously and intervals are equal, all along its range). The slope of the linear function is not an equal-interval variable, neither is the slope defined using percentages. Alternatively, I used a slope defined using sexagesimal degrees, which is equal-interval.

Definition of the problem

The adverse implication of the implementation of a 'slope' variable expressed in sexagesimal degrees, for the simultaneous representation of two 'complementary' time series, is that to incorporate the dataset into cluster analysis, the datasets have to be limited to varying up to 180°. The reason is that distances higher than 180°, even though increasing numerically (180°<181°<182°), are actually decreasing (180°>|180°-181°|>|180°-182°|) when it is taken into account that this variable is defined along the perimeter of a circumference.

The problem is that software implementations of classical hierarchical clustering do not have the means to identify this kind of variable and process them appropriately.

Solutions

The problem can be solved by using a different model (different features), in which case one has to be careful that the variables are necessary, sufficient, and meaningful, that they vary continuously, are equal-interval, and do not introduce 'new' problems. Or, alternatively, to compute the distance matrix by solving the Euclidean distance equation by programing the independent solution of each term (i.e.: the distances defined, along each variable independently), and putting them together afterward (adding them and computing the square root, equation 1).

Equation 1

$$d_{ij} = \sqrt{(p_i - p_j)^2 + (q - q_j)^2 + (r_i - r_j)^2 + (r_i - r_j)^2}$$

Where d_{ij} is the Euclidean distance between two entities, which vary from i (and j), up until n (the size of the dataset), and p_x, q_x, r_x, and, s_x are the corresponding values for each of the variables included in the cluster analysis (model features), for each entity.

Consequences for the present study

It is important to note that the effects of this error will be confined to one term (i.e.: one variable) in the Euclidean equation above. Therefore, the contribution of these errors will be attenuated by the contributions of the other variables and by the computation of the square root. Also, the precise numerical effect of this error will only be known when the correct computation is implemented.

Overall, this error only affected 0.5% of all the distances computed for the cluster analysis (38 out of 7503). The main effect of this error might be changing the position of the U.K. (C15) in the cluster dendrogram, without affecting its relationship to all other clusters. The reason for this is that the U.K. was already a single-country branch, the largest effect of the error occurs between it and C13, and the *de facto* trajectories of the U.K. and the members of C13 (Figure 4) were already extremely contrasting as described in section 3.2.4.

The effect of all other errors may be trivial, as they occur among the most separated countries along the slope variable and are relatively small (max = 6.2% relative to 180°, Table 4).

Table 4 Distances affected by inadequate processing of the slope

Distance types	Averages per error type					No. errors
	correct distance	erroneous estimate	error size relative to 180°	percentage relative to 180°	S.D.	
A	122.0	238.0	58.0	32.2	13.5	5
B	174.7	185.3	5.3	3.0	3.3	18
C	168.9	191.1	11.1	6.2	0.9	12
D	177.7	182.3	2.3	1.3	1.0	3
					Total	38

A: C15 (U.K.) to C13 (Germany, France, Hungary, Bulgaria, and Romania)
B: C15 (U.K.) to 18 countries (Belgium, Egypt A.R., Greece, Spain, China, Portugal, Dominica, Bermuda, Malta, India, Israel, Sri Lanka, Italy, Barbados, Denmark, Lebanon, Austria, and South Korea)
C: Luxembourg, Uruguay, Norway, and Burundi to Hungary, Bulgaria, and Romania
D: Uganda to Hungary, Bulgaria, and Romania

APPENDICES

Appendix 1 NFA as a tool for tracking sustainability

Above I referred to the NFA as a sustainability 'metric', this is a short-hand that has often been used to refer to it. 'Footprint' is today a term that travels across technical, advocacy, and lay vocabularies referring loosely to multiple applications derived from the work by Wackernagel and Rees from 1996 [239]. More precisely, on the one hand, 'footprint analysis' or 'footprinting', refers to a general approach for accounting for, and communicating, the extent of resource requirements of a product or a process (see [240]for a systematic attempt at an analysis of the extent of the application of this terminology). On the other hand, NFA are one specific application maintained and standardized by the Global Footprint Network–GFN.

NFA are an accounting framework, where the supply and demand of production directly dependent on living systems, i.e.: the production from croplands, grasslands, forests, fisheries, and the capacity of forests to sequester carbon dioxide (CO2) are differentially aggregated into two measures, Biocapacity (BC) and Ecological Footprint (EF), respectively, to obtain a balance at the national level. For authoritative descriptions of the methodology see [155,156,177].

As an accounting framework, NFA are not a 'composite index'. This is because, the values being added are not dimensionless, and the rationale behind adding them is not arbitrary. To achieve this, the "extent of land and sea area used – or physical area" of each 'area use' type, is combined with "how much ecological production is associated with that land [or sea area]" into a "standardized – cross-country comparable – unit of measure", global hectares –gha [156]. It is important to note that this means that the NFAs' component measurements correspond to flows, that is, they refer to the amount of ecological production circulated (produced or consumed) by the specific number of equivalent gha on a yearly basis [155,241]. gha do not refer directly to the physical area despite the term hectares in the name of the measuring units (this is analogous to how light-years, despite the presence of the term 'years', refer to distance, not time).

There are five main reasons why "[t]he EF has been widely used in the field of ecology and in the environmental social sciences, and is generally regarded as a reliable indicator of anthropogenic pressure on the environment" [242–245][7]. These reasons are: 1) it focuses on biologically productive land as fundamental for the provision of ecosystems' good and services; 2) it is fairly comprehensive as it aggregates in a reasonable and

[7] See also other references to the Ecological Footprint in this thesis.

explicit manner across multiple important land-uses; 3) it accounts for trade-offs among several important "types of environmental exploitation" [244]; 4) it "does not overlook impacts that are externalized by moving production or extraction outside national borders" [244]; and finally, 5) it localizes consumption matching environmental stress with particular, relevant social units of analysis (nations in the case of the NFA).

Despite their broad acceptance, NFAs' components are not without criticism. Some of the criticism addressed at these components are general to aggregate metrics, and to quantitative data. For example, that being aggregated at the national level, these components do not account for within nation distribution and inequality, or that, being "dependent upon the level of accuracy and availability of a wide range of datasets" [156], produced by a multitude of national and international agencies, "most of which do not specify confidence limits" [156], the data may include systematic and non-systematic (single year error) misrepresentations or omissions [185], including, incomplete coverage. A less obvious, but equally important, general criticism of national statistics it that corresponding to formal data collection efforts and identifying with nation/states (including some national territories), they do not inform us about many informal occurrences, nor about the environmental consequences of a diversity of forms of social organization by many peoples, who are only indirectly and partially represented by official national statistics, if at all (uncontacted tribes, multiple nomad groups, first nations, diasporas, etc.).

Known specific limitations of the NFA were compiled by [185], and, most recent criticism of the NFA has been summarized by [200,246]. Of these specific limitations, the one identified by [174] that: "[a]t the global level the Ecological Footprint is telling us nothing more than human activity is responsible for excessive carbon build up in the atmosphere", seems especially relevant to my work. This issue is relevant because it may confound the results of my classification. Regarding this last issue, I believe that:

First, the usefulness of the NFA also must be evaluated below the global level, at the national level, for which they were designed [202]. Second, the incorporation of the terrestrial area into the computation of the NFA may offer insights that focusing exclusively on CO2 or Greenhouse gas –GHG emissions will not, for example, related to the interaction between the NFA and biodiversity and ecosystems [247–254]. And third, consistent with the conclusion that multiple (i.e.: a dashboard, basket, or a suite of) indicators will be necessary to understand and address complex issues, work on useful indicators, including taxonomic explorations, need to continue with many sustainability-related indicators. For example the carbon footprint, independent and aggregate GHG emissions, other terrestrial area metrics (like the human footprint), other medium-specific metrics (like the water footprint), other metrics related to biological production (human appropriation of net primary productivity-HANPP), etc., along with other human and social progress and well-being metrics. Research on the carbon footprint or on GHG emissions should not preclude research on other useful tools, including NFA.

Regarding criticism of the NFA in general, the GFN has demonstrated disposition for public engagement, self-criticism, and reflection, for example, in engaging with critics [202,246,255–257] and, in forums [258–260]. In addition, there is a publicly available program for further improvement [261]. That program is the product of GFN collaborating with external institutions, sympathetic to GFN efforts but carriers of their own perspectives. These and other developments (making almost all the datasets available yearly, starting in 2017, and increasing that availability in 2018), make us confident that further progress to increase the transparency and utility of the NFA and address existing criticism is a serious possibility for the future.

Returning to the issue of 'indicating' sustainability. The ecological balance indicates whether, or not, human demand on ecological assets of a nation is within the limits of the ecological supply of its territory (and human productive activity). Specific individual nations may not need to be ecologically self-sufficient, consider for example city-states, small island nations, or nations in desert or semi-desert areas that may be partially reliant on external trade. Nevertheless, studying the dynamics of this balance and its components in *per capita* terms allows us to observe the evolution of the contribution of each nation to global sustainability, as seen from the idealized perspective of their 'average citizen'. That is, the dynamics of the yearly domestic ecological production nominally available to that, (idealized) citizen, and the dynamics of the yearly ecological consumption nominally available to that 'same' citizen. These two variables are important components of a nation's actual environmental policies, as opposed to policy statements, documents, or even laws and other legal documents[8]. Obviously, even though, sufficiency is an important component of sustainability, and the dynamics of supply and demand for biologically based production are useful to improve our understanding of sustainability at the national level, it is important to remember that these are not the only attributes that can be

[8] This is the limited sense in which the term sustainability is used in this thesis.

studied, nor the only ones that may help understand and facilitate the pursuit of sustainability and other desirable attributes of human and social progress.

Finally, it is important to note that NFA assumes that long-term natural assets (i.e.: natural capital's principal) should not be added to the accounts. This is, that standing stocks of past biological production which constitute the source of current and future biological production are not included in the accounts. The rationale behind this choice is the assumption that 'strong' sustainability under the current extent of global environmental change [129,262] would require satisfying human demand exclusively from current assets (natural capital's interest), i.e.: the yearly flow of ecological production, which corresponds to the BC component of the accounts. At the national level, overshoot, excess EF above BC not accounted by imports may indicate depletion of standing stocks of past biological production.

Appendix 2 Inconsistencies in Niccolucci et al. [38]

The following appendix is based on a study of the 2016 Public Data Package of the Ecological Footprint Accounts [263]. This dataset is different from the one used by Niccolucci *et al.* [168] (in this appendix, Niccolucci *et al.*). The datasets have different temporal (up until 2014 and 2007, respectively) and geographic countries (a few different countries included and excluded). Nevertheless, a recent "comparison of world calculations of biocapacity and Ecological Footprint in gha per person for each of the six editions published between 2012 and 2018" [177], found, "relatively small changes to global results", "relatively consistent [global] timeline results", and that a "similar comparison [to the one elaborated with Ecological Footprint] across editions of the world's biocapacity per person indicates even greater stability in year-to-year results" (in at least one example using country-level data for Germany).

With the previous in mind and based on my own study of three editions of the National Footprint Accounts (2016 - 2018), I am confident about the following, general observations about Niccolucci *et al.*'s method and results (for a brief description of Niccolucci *et al.*'s work see section 1.1).

When reproducing the method by Niccolucci *et al.*, determining "trend similarity" [168], I observed the following:

1. When one parameter (BCP or EFP) has higher values than the other, it is difficult or impossible to identify the trajectory of the lesser parameter using trend similarity.

2. By using trend similarity, it is also difficult to take into account the range of the scale of the trajectories (i.e.: high, intermediate, or low BCP or EFP), this is because different country plots have different scales.

Furthermore, proceeding to reproduce the classification by Niccolucci *et al.*, I found the following inconsistencies:

The metaphor and the graphical representation employed to define the category 'Scissors' implies the crossing of the trajectories of BCP and EFP. This is not the case for many of the countries included in the category by Niccolucci *et al.* The authors, recognized this by stating that "The scissor and wedge profiles are sometimes characterized by the presence of a particular point: where the BC[P] and EF[P] plots cross" and that "it may be assumed that all other countries [where the transition point does not show] experienced their transition point before the 60s". They nevertheless did not create a different category for those countries, and, as can be seen in the first quotation, this problem extends to some countries classified in the Wedge category.

This is problematic because it represents an inconsistent application of their own methodology and because it subsumes at least two different patterns which may be the product of different processes to the same category. Recognizing that some countries transitioned earlier, and others did so later, may be important to understand the underlying processes that caused the transitions.

A similar situation occurs between the 'Parallel' and 'Wedge' categories. According to Niccolucci *et al.*, these categories are distinguished by the rate of decline, mainly of BCP, but to some extent also of EFP. On the one hand, regarding the first category, they state: "BC[P] and EF[P] trends proceed in 'parallel,' with slow or small changes over time. It is particularly relevant in this type that EF[P] increases slowly (less than 20%) even if it reveals higher values than [the] world average".

On the other hand, here is what they wrote about the 'Wedge' category: "The third type or wedge development path (case c) is characterized by a BC[P] which has been rapidly decreasing and an EF[P] which is generally very low and has a more stable trend". Nevertheless, I found that the categories overlap extensively using these criteria (Table 5).

Table 5 Overlap between Niccolucci *et al.*'s 'Parallel' and 'Wedge'

Niccolucci *et al.* (2012) 'Parallel' Countries	**Number of creditor countries ('Wedge' countries)**	
	With a lower rate of BC decline	With a lower rate of EF increase
Australia	27	34
Canada	26	29
New Zealand	24	33
Argentina	6	7*
Sweden	4	33
Uruguay	4	0*
Norway	4	0*
Finland	1	28

* Negative EF change rates.

I agree that the countries included by Niccolucci *et al.* in the 'Parallel' category form distinctive groups within the creditors (see sections 3.2.3, 3.2.4, and appendices 5 and 6). Nevertheless, it seems that the criteria to discriminate these groups are not the ones identified by the authors using trend similarity.

Finally, the 'Descent' category may be the most complicated. On the one hand, I found that of the twenty-one countries that I classified as apparent declines, all but one, are identified as such by Niccolucci *et al.* The exception is South Africa which they place in the scissor category. South Africa effectively transitioned from creditor to debtor early, I coded it as 1964, Niccolucci *et al.* as 1970s. Nevertheless, from the transition on, both EFP and BCP declined.

On the other hand, I note that all thirty-one countries (included in the 2016 data package) classified by Niccolucci *et al.* in the category 'Descent', belong simultaneously to one of the other three categories ('Parallel', 'Wedge', or 'Scissor'). This is, what they present as mutually exclusive categories, completely overlap. Furthermore, I found that Niccolucci *et al.*, opposite to their criterium, classified as 'Descent' at least twelve countries where one variable is increasing! These are two creditors with increasing EFP (Mali and Timor-Leste), six recent debtors where EFP is increasing (Philippines, Dominican Republic, Lesotho, Indonesia, Burkina Faso, and Yemen, Rep.), and four historical creditors, Ethiopia where BCP is increasing, and Albania, Bangladesh, and Nepal, where EFP is increasing. From the group listed in this paragraph, following Niccolucci *et al.*'s method, I only identified as apparent declines three countries (Nepal, Lesotho, and Burkina Faso).

The inconsistencies that I found in reproducing Niccolucci *et al.*'s "trend similarity" method, could be easily overlooked by accepting their classification uncritically. Ultimately, that classification served the purpose of their paper. Many of the groups that they associate with some criteria, probably do exist but are identified by different benchmarks. This is even more apparent if one considers the more detailed classification that the authors present in their table 1 but which they do not describe in detail in the methodology and where the BCP and EFP classification is confounded by the other variables in their analysis. Furthermore, I acknowledge that the purpose of Niccolucci *et al.* was not to develop a detailed classification of countries by EFP and BCP.

Nonetheless, for these reasons, in this thesis, I take into consideration these 'inconsistencies' and I move forward to contribute to the specific goal of a detailed classification based on EFP and BCP.

Appendix 3 Extended description of the results of trend analysis

Out of the 246 time-series evaluated (one BCP and one EFP time-series for each of 123 countries), 222 are either monotonic ($p < 0.01$ ***, n = 160), very likely monotonic ($p < 0.05$ **, n = 18), likely monotonic ($p < 0.1$*, n = 14), and trend-stationary ($p > 0.1$, n = 30), or stationary ($p < 0.01$ ***, n = 4). Of the remaining twenty-four time-series, seven have clear trends despite the presence of outliers and were correctly identified by the statistical tests (remember that in the KPSS test the null hypothesis is defined contrary to prevalent practice, i.e.: H_1: is unit-root, not trend-stationary). Sixteen were conservatively dismissed using the statistical test. Nevertheless, their behavior is consistent with their later classification, and their classification seems robust to their year-to-year variation. Finally, only one time-series is problematic. As stated in the text:

> "The EFP of Jamaica has a 'light' upward trend, consistent with its later classification, but it is unstable (affected by year-to-year variation). This can make the classification of Jamaica unstable, oscillating between two clusters, nevertheless, this occurs between the two largest clusters (C10 and C12), which are also among the closest (and share historical, economic, and geographic characteristics, compatible with Jamaica)".

The reason for this instability is that even though its trend in Biocapacity is clear, the overall change in both variables is very small, and the year-to-year variation of its EFP is large enough, to affect the slope for the overall trajectory. The previous suggests that line-segments are adequate characterizations for all but one trajectory, with minimal consequences for the classification in general, and even for that exception.

While I demonstrated that the time-series behave as expected, following determinate trends. The suit of statistical tests performed demonstrated to be too conservative. This was in part because, regarding the quality of the monotonicity tests, I preferred the results provided by the correction formulated by Hamed and Rao [187], and those of Mann-Kendall (for non-auto-correlated time-series), to those of the Spearman rank correlation. The latter was less conservative more frequently (rejected the null hypothesis of ϱ (rho) = 0, i.e.: random association, n = 20), and only once was slightly more conservative (i.e.: rejected the null hypothesis under a lesser level of significance). In any case, sixteen of the seventeen negative or inconclusive statistical results turned out to be trivial. These results were mostly the consequence of high year-to-year variation (relative to the mean for stationary series or, relative to the trend for monotonic series). Only in one case (Biocapacity of Vietnam), it was due to a complex (quadratic) but, nevertheless, weak trend (small in overall variation). All outliers (n = 7), either coincided with the trend or could be deemed negligible in the context of the present analysis.

More broadly, this result suggests that neither technological nor social-political or other events have, so far, effectively changed the direction of the trends in BCP and EFP of all tested nations between 1961 and 2014, making the period broadly homogeneous from this point of view, i.e.: demonstrating business-as-usual.

Appendix 4 Clustering dendrograms, 'trees'

Figure 7 Clustering dendrogram without AU values

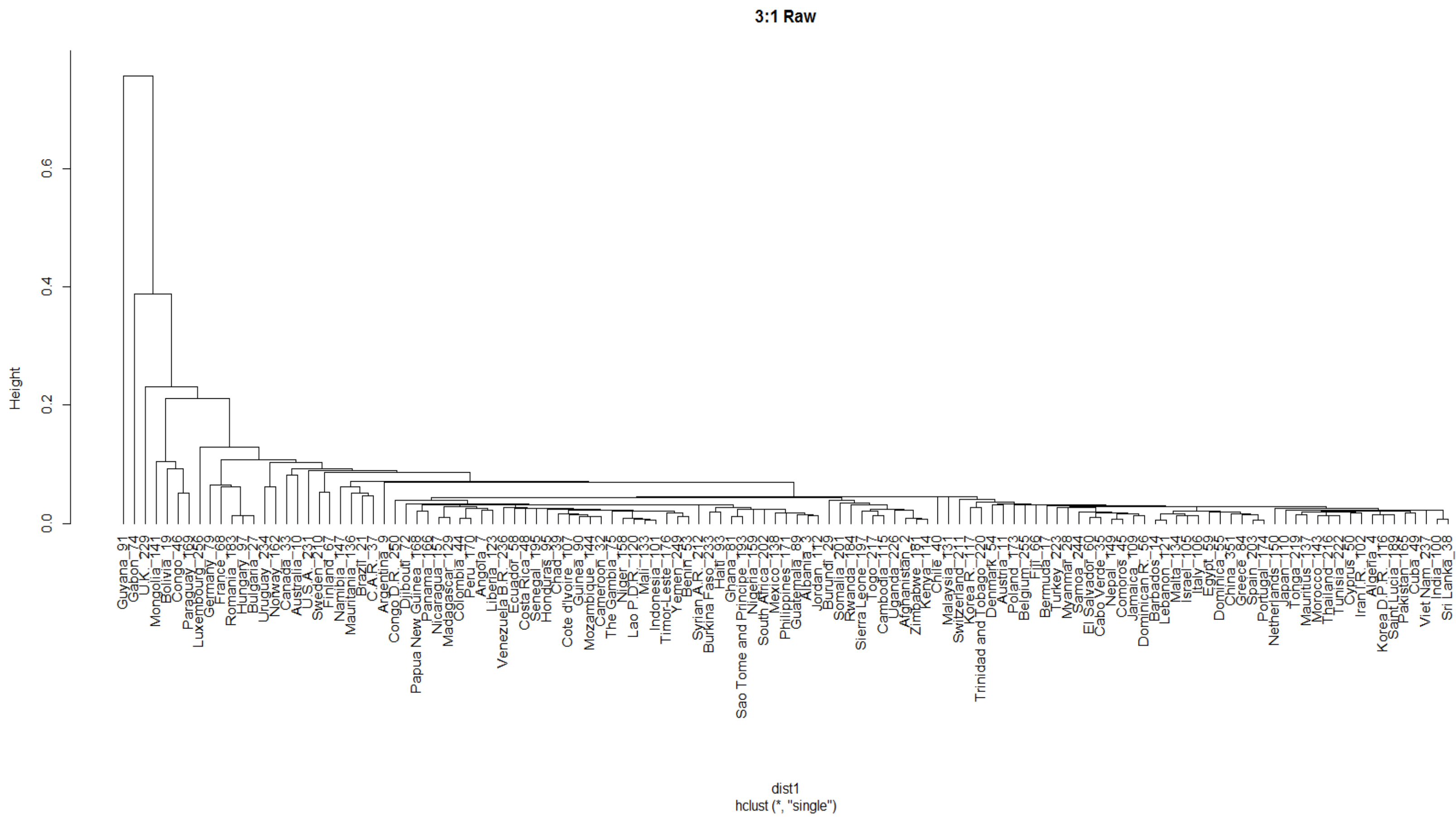
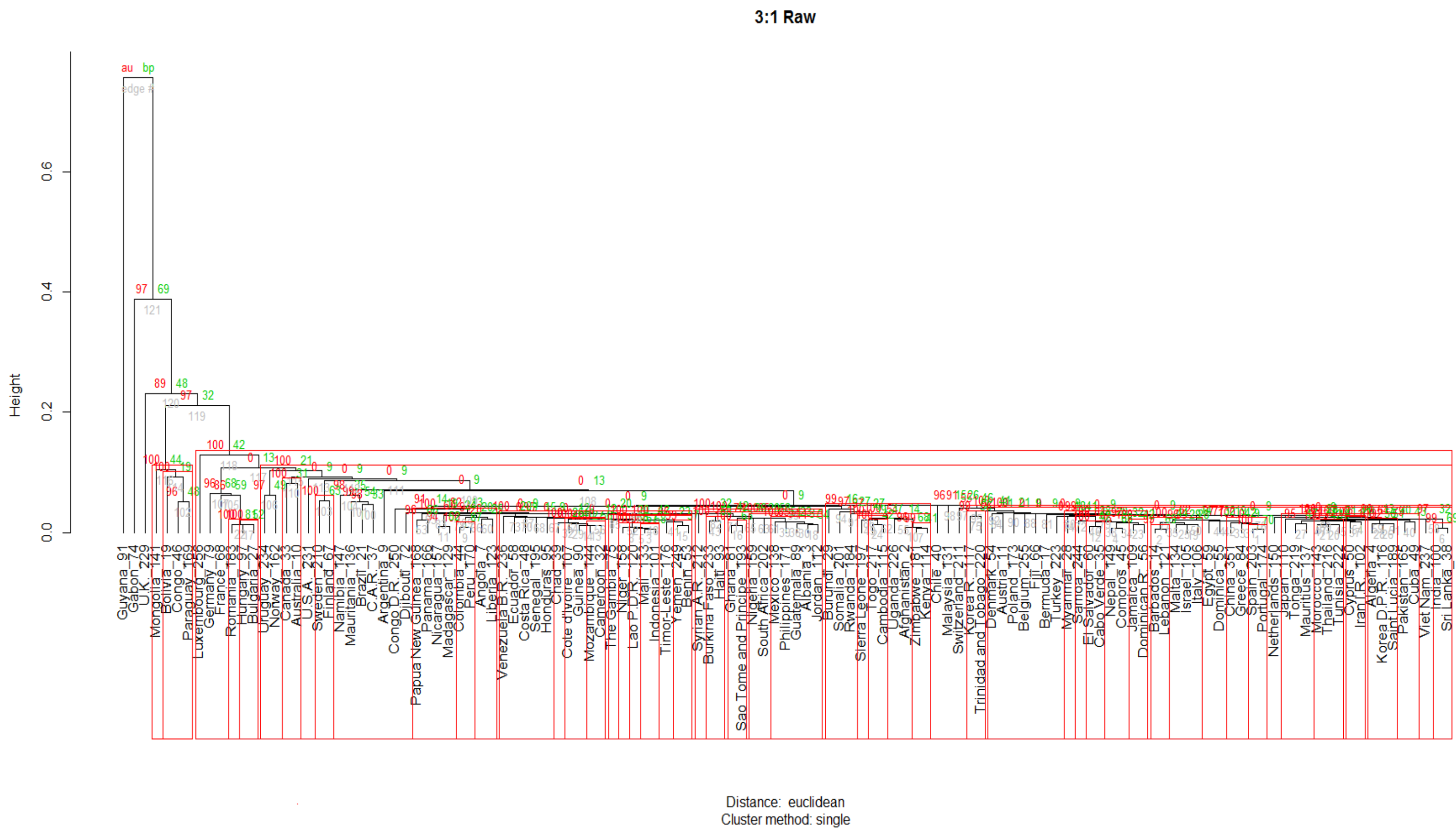


Figure 8 Clustering dendrogram with AU values.

AU: red numbers, red rectangles highlight clusters with AU higher than 0.99



Appendix 5 Detailed taxonomy

Table 6 Negative Balance Trade-Off (NBTO) clusters

Notice that there is not a Recent Creditor column in this table. Data for each country are: Slope (^{o}), BCP (gha/person), EFP (gha/person), and WBIC.

	Historical Debtor	Recent Debtor	Historical Creditor
C1			GY Guyana 178.7 68.80 2.87 LM
C2			GA Gabon 178.6 25.70 2.72 UM
C3			BO Bolivia 178.5 16.49 3.07 LM
			CG Congo R. 179.6 10.49 1.21 LM
			MN Mongolia 176.4 14.96 9.50 UM
			PY Paraguay 180.2 10.37 3.68 UM
C4			NO Norway 222.0 7.41 6.03 H
			UY Uruguay 221.6 10.32 2.98 H
C5			AU Australia 182.1 13.25 6.89 H
			CA Canada 176.8 15.25 8.05 H
C6	US U.S.A. 167.6 3.58 8.37 H		
C7			FI Finland 200.6 12.86 6.09 H
			SE Sweden 196.5 9.74 6.59 H
C8			BR Brazil 177.2 8.85 3.08 UM
			CF C.A.R. 180.0 7.36 1.12 L
			MR Mauritania 184.9 4.35 2.30 LM
			NA Namibia 179.7 6.52 2.09 UM
C9			AR Argentina 181.4 6.71 3.69 H

Table 6 Negative Balance Trade-Off (NBTO) clusters (continued)

	Historical Debtor						Recent Debtor						Historical Creditor					
C10	AL	Albania	159.5	1.05	2.14	UM	BF	Burkina Faso	166.6	1.11	1.31	L	AO	Angola	174.8	2.29	1.56	UM
	HT	Haiti	167.5	0.32	0.67	L	BJ	Benin	179.0	0.94	1.36	L	CD	Congo D.R.	181.0	2.68	0.76	L
	JO	Jordan	160.1	0.21	2.14	UM	CR	Costa Rica	176.1	1.58	2.51	UM	CI	Cote d'Ivoire	182.8	1.97	1.30	LM
							DJ	Djibouti	168.3	0.75	2.94	LM	CM	Cameroon	180.4	1.68	1.27	LM
							GH	Ghana	151.2	1.36	1.96	LM	CO	Colombia	182.1	3.71	1.91	UM
							GM	The Gambia	182.8	0.71	0.96	L	EC	Ecuador	171.7	2.07	2.04	UM
							GT	Guatemala	160.9	1.05	1.84	LM	GN	Guinea	182.9	1.99	1.46	L
							ID	Indonesia	174.2	1.27	1.61	LM	HN	Honduras	191.3	1.73	1.66	LM
							ML	Mali	173.6	1.51	1.54	L	LA	Lao P.D.R.	173.6	1.83	1.78	LM
							MX	Mexico	162.7	1.20	2.55	UM	LR	Liberia	180.3	2.43	1.20	L
							NE	Niger	176.0	1.43	1.76	L	MG	Madagascar	187.3	2.49	0.98	L
							NG	Nigeria	152.5	0.70	1.12	LM	MZ	Mozambique	179.5	1.90	0.87	L
							PH	Philippines	158.3	0.58	1.10	LM	NI	Nicaragua	186.9	2.21	1.48	LM
							SN	Senegal	188.7	0.98	1.11	LM	PA	Panama	179.1	2.89	2.32	UM
							ST	Sao Tome and Principe	152.6	1.02	1.79	LM	PE	Peru	183.5	3.79	2.29	UM
							SY	Syrian A.R.	145.0	0.51	1.46	LM	PG	Papua New Guinea	176.1	3.83	1.85	LM
							VE	Venezuela B.R.	168.0	2.69	3.27	H	TD	Chad	185.4	1.99	1.64	L
							YE	Yemen	178.2	0.43	1.01	LM	TL	Timor-Leste	176.7	1.69	0.57	LM
							ZA	South Africa	158.1	1.08	3.42	UM						
C11	BI	Burundi	222.4	0.32	0.60	L	AF	Afghanistan	208.2	0.50	0.77	L	SL	Sierra Leone	195.6	1.25	1.23	L
	RW	Rwanda	189.5	0.47	0.78	L	KE	Kenya	207.6	0.53	1.04	LM						
	TG	Togo	199.6	0.54	1.11	L	KH	Cambodia	202.0	1.11	1.32	L						
	UG	Uganda	213.1	0.55	1.19	L	SO	Somalia	202.0	1.18	1.21	L						
							ZW	Zimbabwe	205.9	0.54	1.09	L						

Table 7 C12 (mostly PBTO) and related clusters, C13 to C15

PBTO: Positive Balance Trade-Off. Notice there is not a Recent Creditor column in this table. Data for each country are: Slope (^{o}), BCP (gha/person), EFP (gha/person), and WBIC.

	Historical Debtor						Recent Debtor						Historical Creditor					
C12	AT	Austria	96.3	3.01	5.88	H	CL	Chile **(1)**	150.3	3.47	4.03	H	MM	Myanmar	135.1	1.88	1.55	LM
	BB	Barbados	95.8	0.16	3.55	H	CN	China	90.0	0.98	3.71	UM						
	BE	Belgium	87.0	0.94	6.71	H	CV	Cabo Verde	125.6	0.60	1.63	LM						
	BM	Bermuda	91.0	0.14	6.78	H	DM	Dominica	90.4	1.05	2.53	UM						
	CH	Switzerland	120.4	1.09	4.85	H	DO	Dominican R.	130.5	0.60	1.59	UM						
	CU	Cuba	112.0	0.80	1.91	UM	DZ	Algeria	117.8	0.54	2.45	UM						
	CY	Cyprus	108.0	0.24	3.32	H	FJ	Fiji	130.8	2.37	3.90	UM						
	DK	Denmark	95.8	4.43	7.13	H	IR	Iran I.R.	109.8	0.76	3.40	UM						
	EG	Egypt A.R.	87.6	0.47	1.98	LM	KM	Comoros	134.1	0.33	0.85	L						
	ES	Spain	89.2	1.33	3.81	H	KP	Korea D.P.R.	113.7	0.59	2.87	L						
	GR	Greece	88.0	1.60	4.29	H	KR	Korea R.	97.3	0.69	5.82	H						
	IL	Israel	93.9	0.27	4.68	H	LC	Saint Lucia	115.0	0.32	2.05	UM						
	IN	India	93.9	0.45	1.12	LM	MA	Morocco	104.7	0.77	1.75	LM						
	IT	Italy	94.2	0.94	4.29	H	MU	Mauritius	103.9	0.71	3.50	UM						
	JM	Jamaica	127.8	0.42	1.77	UM	MY	Malaysia **(1)**	141.0	2.39	4.42	UM						
	JP	Japan	103.2	0.60	4.74	H	SV	El Salvador	123.9	0.61	2.00	LM						
	LB	Lebanon	95.9	0.31	3.35	UM	TH	Thailand	104.9	1.27	2.49	UM						
	LK	Sri Lanka	94.2	0.48	1.53	LM	TN	Tunisia	107.0	0.79	2.17	UM						
	MT	Malta	92.8	0.62	4.89	H	TO	Tonga	102.5	1.59	3.30	UM						
	NL	Netherlands	99.1	0.86	5.92	H	TR	Turkey	128.0	1.44	3.21	UM						
	NP	Nepal	133.2	0.61	1.03	L	TT	Trinidad and Tobago	100.9	1.56	6.69	H						
	PK	Pakistan	111.2	0.40	0.79	LM	VN	Viet Nam	99.2	1.05	1.73	LM						
	PL	Poland	99.9	2.08	4.44	H	WS	Samoa	123.3	1.88	2.39	LM						
	PT	Portugal	90.2	1.27	3.69	H												

Table 7 C12 (mostly PBTO) and related clusters, (C13 to C15 (continued)

Notice the Historical Creditor column has been replaced by a Recent Creditor column in the following table. There are no Recent debtor nor Historical Creditor columns in this table.

	Historical Debtor						Recent Creditor					
C13	DE	Germany	61.0	1.79	5.05	H	BG	Bulgaria **(2)**	31.1	3.34	3.17	UM
	FR	France	45.5	2.73	4.70	H	RO	Romania **(2)**	31.6	2.88	2.80	UM
	HU	Hungary **(2)**	29.6	2.68	3.60	H						
C14	LU	Luxembourg **(1)**	221.5	1.38	12.28	H						
C15	GB	U.K. **(3)**	277.8	1.21	4.80	H						

(1) NBTO: (Chile and Malaysia in C12 and Luxembourg inC14)

(2) BC and EF increase, slope lower than PBTO (Hungary, Bulgaria, and Romania in C13)

(3) BC increase and EF decrease, slope much higher than NBTO (U.K. in C15)

Appendix 6 Main branches (C1 – C15) descriptions

In the following, are the particularities of each branch. Units for values in parenthesis are gha/person and correspond to 2014 records unless otherwise stated:

C1 (Guyana): had the largest BCP in 1961 (101.3) and 2014 (68.8), and a very large decrease of BCP over the period (-32.5). EF is intermediate (2.9). It is a historical creditor.

C2 (Gabon): had the second-largest BCP in 1961 (87.3) and 2014 (25.7), and the largest decrease of BCP over the period (-61.6). EFP is intermediate (2.7). It is a historical creditor.

C3: corresponds to four countries with very high BCP in 1961 (44.2 to 53.1), topped only by Guyana and Gabon, and very high BCP decreases (-38.1 to -33.8), topped only by Gabon. It includes the Republic of Congo, Bolivia, Paraguay, and Mongolia. The EFP of Mongolia is notably high (9.5), that of others is low to intermediate (1.2, 3.0 and 3.7). This characteristic disaggregates the group in the next (lower) clustering branch. All countries are historical creditors.

C4 (Uruguay and Norway): these two countries exhibit relatively high BCP (10.3 and 7.4), intermediate to high EFP (3.0 and 6.0), some of the smallest losses of BCP relative to their reference value of 1961 (-1.8 and -

2.35), and the largest losses of EFP (-1.6 and -2.1). Both countries are historical creditors.

C5 (Canada and Australia): these two countries exhibit high BCP (15.2 and 13.3), significant decreases of BCP (-11.0 and -15.9), and High EFP (8.0 and 6.9). Change in EFP has been very small (0.6 and -0.6). Both countries are historical creditors.

C6 (U.S.A.): exhibits intermediate BCP (3.6) and high EFP (8.4) it has had relatively small decreases of BCP (-1.42) and negligible (positive) change in EFP (0.31). Of the countries with NBTO and High EFP, it has the lowest BCP and is the only historical debtor (the only large, wealthy country, and the only large 'new world' country that is a historical debtor).

C7 (Finland and Sweden): These two countries exhibit high BCP (12.9 and 9.7) and High EFP (6.1 and 6.6) with small to intermediate decreases of BCP (-3.1 and -1.7), like those of Uruguay and Norway and much smaller than those of Canada and Australia. Change in EFP has been small (-0.6 and -0.9). Both countries are historical creditors.

C8: Corresponds to four countries with relatively high BCP (4.4 to 8.9) and High BCP decreases (-13.9 to -19.9), nevertheless, in both cases with values lower than those found in C3. This cluster includes the Central

African Republic, Mauritania, Namibia, and Brazil. EFP is intermediate (1.1 to 3.1). All countries are historical creditors.

C9 (Argentina): it has relatively high BCP (6.7), intermediate BCP losses (-3.7), and intermediate EFP (3.7), with almost no change (-0.1). The combination of characteristics is what makes it unique. It is a historical creditor.

C10: The second-largest cluster (n = 40). Compared to branches C1 - C9 countries in this cluster tend to have lower BCP (0.2 to 3.8). Compared to cluster C12 countries in this branch have had greater decreases of BCP relative to their change in EFP (θ: 145° to 191°). Twenty countries in this cluster are from Africa and eleven are from America. Eighteen countries are historical creditors, nineteen are recent debtors, and only three countries are historical debtors (Haiti, Albania, and Jordan). Albania is the only European country in the cluster, and outside the small and single-country branches and of clusters C12 and C13.

C11: The third cluster in size (n = 10). all countries in this cluster have BCP and EFP below world average BC (1.71) and have both decreasing BCP and EFP. Eight of these countries are in Africa (Burundi, Kenya, Rwanda, Sierra Leone, Somalia, Togo, Uganda, and Zimbabwe), the others are Cambodia and Afghanistan. Four countries are historical debtors, five are recent debtors and only one is a historical creditor. Five of these countries are landlocked. The trajectory of these countries corresponds to what was termed "descent" in Niccolucci *et al.* [168].

C12: The largest cluster (n = 48). The main characteristic of this cluster is that countries exhibit relatively large increases of EFP coupled with comparatively small changes in BCP (increases or decreases, θ: 87° to 150°). BCP varies from very low to intermediate-high (0.14 to 4.43). EFP varies from very low to high (0.79 to 7.13). Twenty-four countries are historical debtors, twenty-three are recent debtors, and only one is a historical creditor (Myanmar). Twelve out of twenty-three European countries are found in this cluster.

C13: Corresponds to five European countries, including the only two recent creditors in the dataset (Bulgaria and Romania), and three historical debtors (Hungary, France, and Germany). These countries have had the largest increases in BCP (which are nevertheless small: 0.43 to 1.16), coupled with increases in EFP (0.3 to 0.8). BCP is intermediate (1.8 to 3.3), and EFP is intermediate to intermediate-high (2.8 to 5.0). The situations of Bulgaria, Romania, and Hungary have been identified with sub-replacement fertility rates, out-migration, and temporary decreases in life expectancy that have been outcomes of the conditions before the revolutions of 1989 and of their aftermath up until today [264–268]. These conditions may affect similarly, other eastern European countries not included in my analysis because of their truncated time-series starting in 1991.

C14 (Luxembourg): This country is notable for the highest EFP in 1961 (13.3) and 2014 (12.3). The trajectory of this country resembles those of countries in C11 (decreasing both BCP and EFP), the difference is that its EFP corresponds to between 9.5 and 20.5 times the EFP of the countries in that cluster. This country should also be identified as "descent" following Niccolucci *et al.*[168]. BCP is low (1.38). It is a historical debtor.

C15 (U.K.): It is the only country outside C13 exhibiting increases of BCP, albeit the smallest (0.18). Therefore, it is the only country exhibiting an increase of BCP with a simultaneous decrease of EFP (-1.35). It has low BCP (1.21) and intermediate-high EFP (4.8). It is a historical debtor.

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