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Learning from nature to reconcile economic upgrading with biodiversity conservation? Biomimicry as an innovation policy

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Abstract

One of the most important challenges of the 21st century is the quest for development models that enable to sustain livelihoods while respecting the planet's ecology. Rather than imposing our industrial systems on nature, why not let nature influence our industrial and innovation systems?

This research investigates the role of biomimicry-based innovation strategies to support industrial and technological development while ensuring the protection of natural ecosystems. From wind turbine blades to bullet trains and solar cells, many of the technologies we rely on today have been inspired by solutions found in nature. However, biomimicry/biomimetics remains largely overlooked in the development and innovation economics literature. This is paradoxical because, as this paper shows, the biodiversity stock in developing countries is a knowledge bank of solutions to both current challenges as well as unknown problems of the future. Leveraging such information stock, through biomimicry, provides a valuable opportunity for economic upgrading in those nations.

Several findings arise from this study. First, despite the exponential growth of biomimicry as a field and our understanding of its economic impact, what drives nature-inspired innovation remains elusive. Second, the biomimicry innovation landscape is dominated by advanced economies that have relied on proactive policy interventions, while virtually no developing country has adopted biomimicry as an innovation strategy. Third, by drawing on empirical evidence from a selection of Latin American countries, this paper shows that while biomimicry presents tremendous opportunities to leapfrog towards high value-added sectors by using local biodiversity and related expertise as factor endowments, the lack of policy and institutional support has led to the persistence of important coordination failures. This paper concludes by discussing the type of public policies needed to support the integration of developing nations at the innovation frontier through biomimicry.

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"Imitation is not just the sincerest form of flattery - it's the sincerest form of learning."
— George Bernard Shaw

"Learn from nature: that is where our future lies"
— Leonardo Da Vinci

1. INTRODUCTION

To tackle climate change, considerable efforts need to be deployed towards biodiversity protection. But how can countries generate prosperity while ensuring biodiversity protection? More precisely, how can developing countries benefit economically from the changing sustainability and innovation landscape? This paper tackles some of these salient questions by identifying biomimicry as a pathway for aligning innovation, economic development, and biodiversity protection objectives.

Biomimicry is an innovation method which relies on the inspiration, learning from, and imitation of the strategies found in nature to solve human design challenges (e.g., solar cells that mimic leaves) to create a healthier, greener, and more sustainable future (Benyus, 1997). From the kingfisher-inspired design of the design of Japanese bullet trains; the burrs-inspired invention of Velcro, and wind turbine blades whose shapes are inspired by the ridges on the pectoral fins of humpback whales that create an aerodynamic flow in water, many of the technologies we rely on today have been influenced by solutions found in nature. Our natural environment has inspired design since prehistoric man fashioned spears from the teeth of animals, but the development of a methodological framework for translating biological strategies into design innovations is a recent one (Kennedy et al, 2013). Biomimicry is aligned with the idea that the 3.8 billion years of evolution have produced optimised designs and solutions within our natural ecosystem which can often provide better alternatives to technologies used today (Biomimicry Institute, 2020). Acting as natural R&D, evolution has selected the most efficient and optimal designs and discarded the non-functional ones (Pawlyn, 2016).

The study of biomimicry is relatively widespread in the field of architecture and engineering (e.g. Altomonte, 2008; Oxman, 2011; Rao, 2014; Zari, 2010; Fecheyr-Lippens and Bhiwapurkar, 2017) but remains much less studied in the economics and public policy literatures, and in social sciences more broadly. In addition, the academic discussion on biomimicry and the innovation value of biodiversity in general has rarely considered the context of developing countries.[1] This reflects a more general neglect in the discussion regarding the economic opportunities arising from context the transition to a low carbon economy, which has often focused on developing countries as consumers - rather than producers – of new technologies. By adopting a comprehensive and dynamic analysis of the acquisition of comparative advantages, which considers the role of learning, technological upgrading, productive capabilities, and public policies, this paper investigates how biomimicry can provide opportunities for developing countries to leverage their biodiverse environment as inputs for innovation activities which generate highly skilled jobs and knowledge spillovers (in contrast to ecotourism). More particularly, this paper draws on the rich insights from evolutionary and neo-schumpeterian economics, which focus on innovation dynamics, national innovation ecosystems, changing structures, and disequilibrium processes, to analyse the factors and policies that can help unleash the untapped potential of biomimicry for innovation processes in developing nations. While the policy discussion on biodiversity in developing countries is often limited to its ecological value, this paper also aims to contribute to the existing scholarship that conceptualises the value of biodiversity as a source of information that can feed into industrial and innovation processes (see Weitzman 1992, 1998; Simpson et al. 1996; Swanson 1996; Benyus 1997, Goeschl and Swanson,

[1] Some studies have been conducted in the context of advanced economies (e.g. USA, Germany), and more recently in the case of China (see Fermanian Business & Economic Institute, 2020) and South Korea (Bae et al. 2019; Reaser et al. 2020)

2002; and Pearce and Peace, 2001). Within the literature on the valuation of natural assets, the emphasis on the value of biodiversity as a source of *inspiration* – rather than a source of genetic material that can feed into different R&D processes – constitutes one of the gaps that this paper addresses.

In a context in which sustainability is increasingly considered as the next innovation frontier (Nidumolu et al. 2009), this paper also aims to promote a commingling of different disciplines, to demonstrate to development economists the usefulness of biodiversity protection in the context of economic upgrading, and to environmentalists and ecologists the usefulness of adopting developmental and innovation perspectives in the conservation debates. Although R&D and biodiversity conservation do not necessarily go together, this paper aims to raise awareness on the ways in which biomimicry-based R&D can help support both developmental and conservation efforts, thereby challenging the notion that economic development and sustainability are mutually exclusive.

Section 2 of this paper provide a theoretical discussion on what growing concerns for ecological sustainability imply for the role of innovation for economic upgrading in latecomer economies (developing countries). Section 3 describes the boom witnessed in the biomimicry sector over the last two decades and investigates the opportunities it provides for developing countries. Section 4 provides a landscape of the biomimicry sector across the globe and some of the emerging trends. Biomimicry has developed substantially in North America, East Asia, and Europe thanks to significant policy support and industrial policies. In contrast, very few developing countries have implemented policies that promote R&D in biomimicry, which has generated an even distribution of value within the sector and high entry barriers through an exploitation of northern industries on southern biodiversity. Section 5 provides an analysis of the integration of Latin American firms into the biomimicry value chains and identifies key obstacles. This analysis relies on preliminary data collection that has been conducted through desk-based research and fieldwork interviews in Costa Rica and Ecuador. Section 6 outlines the policy implications of this research. Section 7 provides concluding remarks.

2. INNOVATION (STILL) MATTERS FOR (SUSTAINABLE) DEVELOPMENT IN THE 21ST CENTURY

To highlight the links between present choices and future production possibilities, it is worth investigating what the context of climate change and growing concerns for sustainability imply for the role of innovation and upgrading global value chains as a development strategy in latecomer economies.

A vast body of literature has evidenced the key role of innovation for catch-up growth. In the 1930s, Joseph Schumpeter had already made the distinction between mere growth and structural economic change. He argued that economic development is based on transfers of capital from one sector to another utilizing new technologies and innovative methods (Shapiro and Taylor, 1990). In a departure from existing models of endogenous growth, Aghion and Howitt (1990) have also explained how technological innovations influence economic growth by making use of Schumpeter's concept of creative destruction, the competitive process whereby entrepreneurs constantly seek new ideas that will render their rivals' ideas obsolete.

More recently, in the context of developing countries, several scholars (such as Eichengreen et al., 2012, 2013; and Lee, 2013) have also argued that innovation capabilities are the key binding constraint for escaping the middle-income trap. This view is also consistent with the notion that middle-income economies would tend to fall under a trap because they get caught between low-wage manufacturers and high-wage innovators; their wage rates are too high to compete with low-wage exporters and the level of their technological capability is too low to enable them to compete with advanced countries (World Bank 2010).

The role of innovation for structural transformation remains relevant in the context of low carbon transitions. Sustainability is increasingly considered as the next innovation frontier (Nidumolu et al. 2009) as demonstrated by the growing literature that attempts to bridge the environmental urgency with economic and industrial development.[2] For instance, Porter and van der Lynde (1995) argued that properly crafted environmental standards can trigger innovation offsets, allowing companies to improve their resource productivity. Cantore and Cheng (2018) also argue that environmental policies and industrial policies may not be rival but provide suggestive evidence that environmental market policies may trigger the development of local industrial capabilities. Using data on 1 million patents and 3 million citations, Dechezlepretre et al. (2013) also find that spillovers from low-carbon innovation are over 40% greater than conventional technologies in energy production and transportation sectors. The capacity to innovate, thus, appears to be important for making the most of energy transition as an industrial opportunity, as a source of value creation (and arguably of high-quality job creation). In that perspective, several scholars have emphasized the role of innovation-driven industrial policies in the context of climate change (see Anadon et al. 2016; Barrett 2009; Conchado et al. 2016; Doblinger et al. 2019; Mercure et al. 2016; Naudé 2011). However, the 'innovation' dimension of low carbon transitions is rarely attempted by developing countries (with the notable exceptions of China and Brazil), which has implications for their ability to seize a larger share of the economic benefits of the global green transition (Anzolin and Lebdioui, 2021).

To understand how latecomers can compete at the innovation frontier in the age of sustainability and extend developmentalist perspectives to the context of biodiversity protection, the rest of this paper explores how developing countries can leverage their biodiversity as an innovation tool. By doing so, this paper also builds on the early insights that developing regions such as Latin America should utilize their natural resources to leap forward with the next technological revolution (Perez 2010).

3. LEAPFROGGING THROUGH BIOMIMICRY-BASED INNOVATION

3.1 Biodiversity's value as source of innovation.

There are many ways in which biodiversity can support the economy and human well-being. Beyond the discussions on the ecological value of natural ecosystems, biodiversity can also hold considerable value as a source of information that can feed into innovation processes. Several economists have described the R&D process as one of information utilisation, application and diffusion (e.g. Arrow, 1962) and dependent upon a stock of "information" for its generation of useful innovations (Stoneman, 1983). In that perspective, biodiversity is one of the primary sources of a stock of information that may be accessed for possible solution concepts to socio-biological problems (Swanson 1993).

Biodiversity and environmental assets can generate direct benefits to humankind in the form of new genetic material for drugs, agriculture, and increasingly ecotourism (Pearce and Pearce 2001; Swanson 1996). Environmental assets can also have value as sources of information that can feed into research, innovation, and industrial processes (see Benyus 1997; Simpson et al. 1996; Swanson 1996). Swanson (1997) demonstrates the extent to which biodiversity as is relied on as an input into the R&D process in various industries (e.g. Pharmaceutical and Agricultural industries). This reliance is so substantial that the elimination of biodiversity could be disastrous for these important industries (ibid.).[3] Furthermore, because it is increasingly possible to transfer strategies between organisms and living systems in ways that were not possible in the past, the technological frontier in the area of the bio-industries should dramatically increase the value of biodiversity in the R&D process (ibid.).

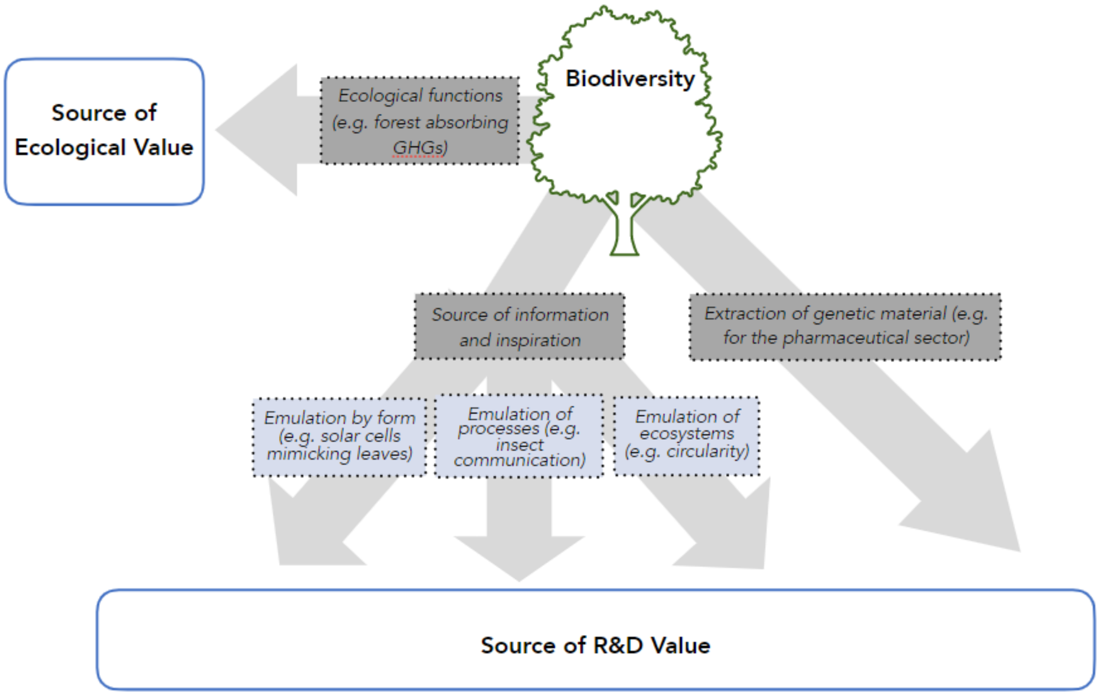
[2] See Porter and van der Lynde 1995; Aiginger 2015; Pollin 2015, Garret-Peltier 2017; Fraccaschia et al. 2018; Fouquet 2019; Filippini et al. 2020; Anzolin and Lebdioui, 2021 for instance.

[3] Indeed, between 25-50% of pharmaceutical products are derived from genetic resources and around 70% per cent of drugs used for cancer are natural or are synthetic products inspired by nature (IPBES Global Assessment on Biodiversity and Ecosystem Services, 2019).

The notion of the value of biodiversity as a source of information for innovation would cut across the different types of values in of Pearce's environmental valuation framework. [4] Indeed, environmental assets that are useful sources of information and inspiration for innovation have direct, indirect, as well as option value (because there is market value in biological information, although it cannot easily be monetised; such assets may be preserved for future use).[5]

We can however further distinguish three main ways in which biodiversity holds value for innovation processes, as mapped out in figure 1 below. Biodiversity can be used as an important information input into innovation processes through its value as a provider of genetic material (as above mentioned) through a process known as *bioprospecting*, but also through its value as a source of inspiration (and can be emulated by form, process, or ecosystem), which leads us to the concept of *biomimicry*.

Figure 1: Mapping the channels between biodiversity and its value as input into R&D processes



Source: Author's elaboration

3.2 Leveraging the innovation value of biodiversity through biomimicry

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[4] In his pioneering work on economic valuation to improve decisions on environmental protection, Pearce (1992) distinguished between direct use value, indirect use value, option value, and existence value of environmental assets. Direct use value is often easily measured in monetary terms and relates to goods that have a direct economic value (e.g., arable land from which agriculture income can be generated). Indirect use value is understood in terms of the 'ecological functions' (e.g., a tropical forest might help protect watersheds, or store carbon dioxide and many species which in turn may have ecological functions) (Pearce 1992). Option value relates to the amount that individuals would be willing to pay to conserve a tropical forest for future use (e.g., salt lakes in Bolivia that attract a large number of tourists every year). Existence value consists of the valuation of an environmental asset because individuals are willing to pay for its mere existence, which is especially the case when such an asset is unique (Pearce 1992).[4]

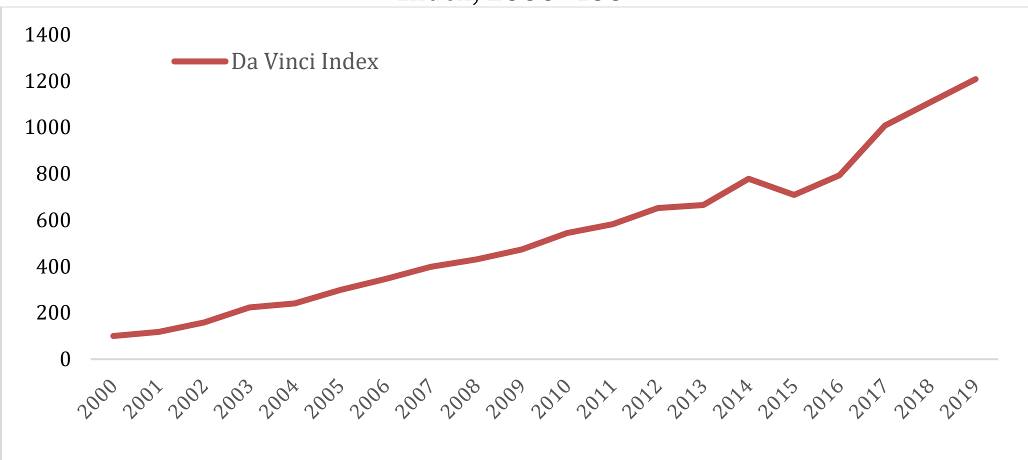
[5] In its different approach to the concept of 'natural capital' which complements the one in Pearce (1992), Bateman and Mace (2012) distinguishes the role of natural assets as an ecosystem service (for example, pollination, pest control and eco-tourism), a supporting role (resilience that is attributable to biodiversity) and in their own right, which is often confused with 'intrinsic value' (Bateman et al. 2011). Natural assets often hold value in their own right, especially as sources of information for innovation.

Biomimicry (also referred to as biomimetics, biodesign, or nature-inspired innovation) involves learning from and emulating biological forms, processes, and ecosystems tested by the environment and refined through evolution (Benyus, 2013). The term 'biomimetics' was coined by Otto Schmitt in the 1960s to describe the transfer of ideas from biology to technology, while the term 'biomimicry' was popularized in the 1990s by Janine Benyus. Biology has inspired design since prehistoric man fashioned spears from the teeth of animals, but the development of a methodological framework for translating biological strategies into design innovations is a recent one (Kennedy et al, 2013). Biomimicry, which implies emulating biology, is different from harvesting organisms to accomplish a desired function, and therefore marks a divergence from the Industrial Revolution, which was "an era based on what we can extract from nature" (Benyus 1997) . Rather than "using an organism to 'do what it does', biomimicry aims to instead leverage the design principles embodied by the organism (Kennedy et al. 2013). This is the equivalent of the difference between using fireflies themselves to produce light, and understanding and applying the complex chemistry involved in bioluminescence (Helms et al. 2009; Kennedy et al. 2013).

Nature-inspired technologies can also play a key role in tackling climate change mitigation with the premise that nature knows best how to adapt to its environment. Biomimicry therefore holds the potential to contribute to the development of technologies that have net zero or net positive environmental consequences because biological solutions have been time-tested by billions of years of evolution and embody successful strategies for thriving on earth (Benyus 2013).

The field of biomimicry has been booming over the past 20 years. There has been a twelvefold increase in biomimicry patents, scholarly articles, and research grants between 2000 and 2019, as shown by figure 2. Between 1985 and 2005, there were proportionally more biomimicry patents filed than other patents (Bonser, 2006), signifying an increased interest and innovation activity in the space. The rate at which patents related to biomimicry were filed also increased rapidly following the 1990s and into the early 2000s (Pawlyn, 2016).

Figure 2: Evolution of biomimicry-related research and patents (Da Vinci Index) Index, 2000=100[6]



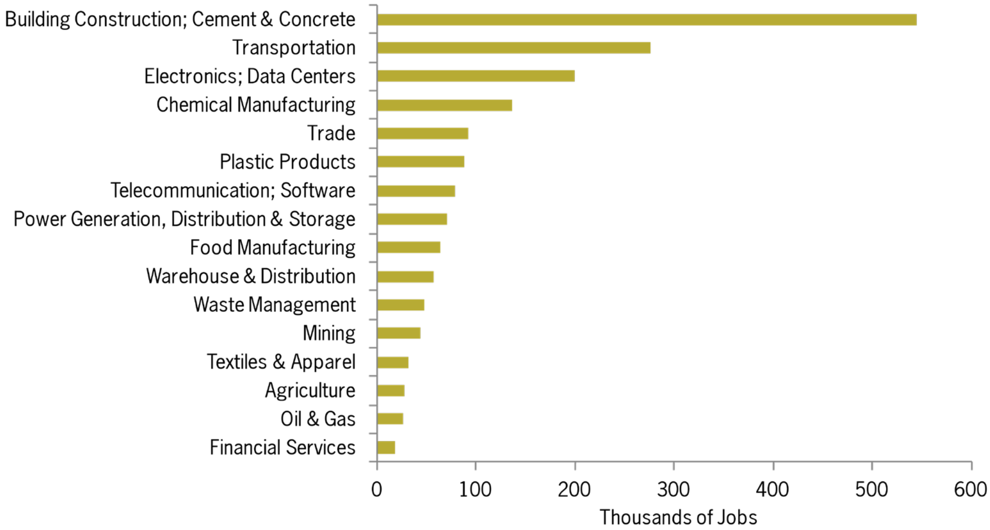
Source: Fermanian Business & Economic Institute

Biomimicry activities can also generate large spill overs in terms in value and employment creation. Estimates from the Fermanian Business & Economic Institute (2013) suggest that biomimicry could account for as much as USD425 billion of the GDP of the United States and USD1.6 trillion of global output by 2030 (ibid). Bioinspired products will increase employment in sectors as diverse as transportation, electronics, and food manufacturing, as it will impact the economic performance in those activities (FBEI 2015). As shown in figure 3, the largest single-

[6] The Da Vinci Index (which was created by the Fermanian Business & Economic Institute and launched in 2011) measures activity in the field of bioinspiration by monitoring the number of scholarly articles, number of patents, number of grants, and dollar value of grants.

industry contributions are expected in the construction, transportation, chemical manufacturing and the power generation, distribution and storage sectors.

Figure 3. Bioinspired innovation's forecasted impact on employment in 2030



Source: FBEI 2015

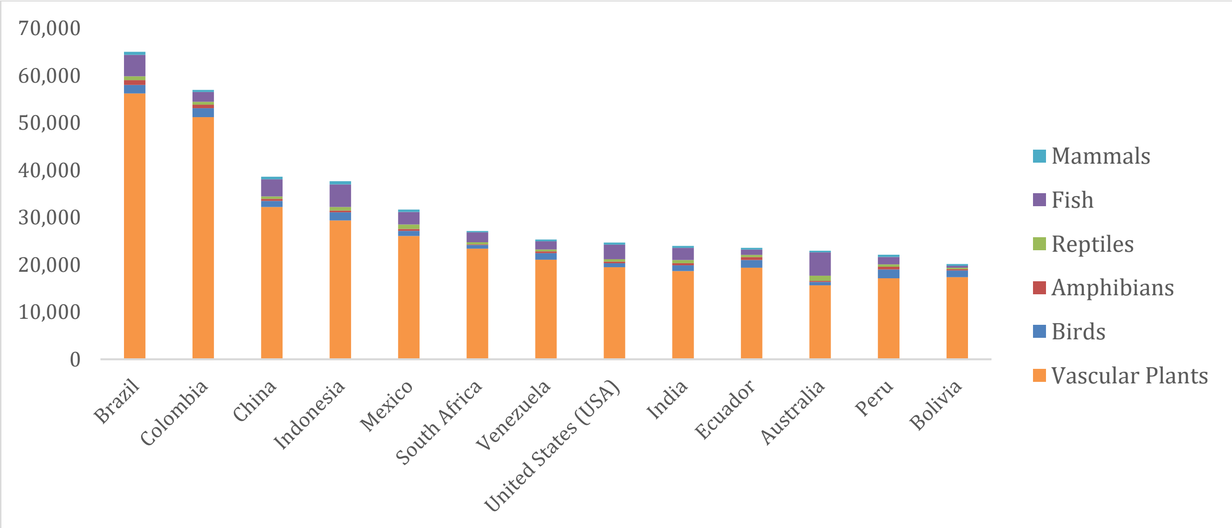
The rapid development of biomimicry as a field is also evidenced by a growing demand for training in biomimicry theory and practice (Lepora et al, 2013). The development and expansion of biomimicry is important and worth investigating not just because of its economic prospects, but- also because of its tremendous potential for biodiverse developing countries to integrate such methods in their innovation and development strategies and processes.

3.3. Opportunities for Developing countries

The development and expansion of biomimicry is worth investigating not just because of its economic prospects (as shown above), but also because of its tremendous relevance in the formulation of development strategies in biodiverse developing countries, as it offers prospects for leveraging local biodiversity as factor endowment for innovation to 'leapfrog' towards high value-added sectors. The fact that the discussion on leveraging the innovation value of biodiversity has overlooked the context developing countries is particularly paradoxical since most of the existing biodiversity hotspots are in the developing world (in Latin America, Central Africa, and South East Asia more specifically) as shown in figures 4a and 4b.

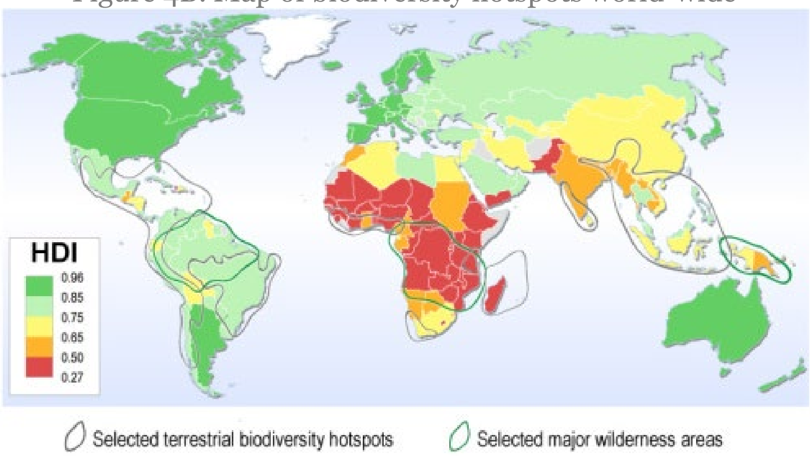
Figure 4: The Developing world's lion share of (remaining) biodiversity

Figure 4A. Biodiversity Index based on the total number of amphibian, bird, fish, mammal, reptile, and vascular plant species, by country



Source: Data compiled in Mongabay, using Plant data from the World Conservation Monitoring Centre of the United Nations Environment Programme (UNEP-WCMC), 2004; Species Data from Fish: Fishbase; Birds: Birdlife International; Amphibians: AmphibiaWeb; Mammals: IUCN; Reptiles: the Reptile Database.

Figure 4B. Map of biodiversity hotspots world-wide



Source: UNDP (2004); Conservation International (2004)

There is also a vast body of local (and often indigenous) knowledge of biodiversity processes in several developing regions that has often been neglected in innovation and development processes. For instance, the considerable experience of Latin American researchers, firms and communities in the discovery and mapping of fauna and flora could provide related capabilities for biomimicry activities. The theory of product-relatedness by Hausmann and Klinger (2007) is based on the notion that every product requires capabilities (knowledge, physical assets, intermediate inputs, labour-training requirements, infrastructure needs, property rights, regulatory requirements and so on) that are highly specific to that activity and sector. If two goods need the same capabilities, a country that has a comparative advantage in one would be well position to acquire a comparative advantage in the other (ibid.). In that sense, it can be argued that the local knowledge regarding environmental assets and their usefulness can represent a source of comparative advantage that can be leveraged by biomimicry-focused national innovation ecosystems. However, such domestic knowledge of biodiversity has often being extracted by foreign firms without recognition nor compensation, as shown by the increasing number of complaints against biopiracy in developing nations. Biopiracy is practice in which indigenous knowledge of nature, originating with indigenous peoples, is used by others for profit, without authorization or compensation to the indigenous people themselves (EJOLT, 2015). Biopiracy most often benefits firms located in advanced economies. For instance, a recent report from the Ecuadorian government found that the United States, Germany, the Netherlands, Australia and South Korea as the five countries that requested most patents for products derived from Ecuador's endemic resources (Senescyt, 2016). So-called "biopirates" in these countries did not request authorisation from Ecuador to access the genetic resources used in these patents. If we consider that Southern biodiversity represents the source of inspiration for the global nature-inspired technological innovation landscape, the provision and maintenance of biodiversity in developing countries could be compared to the supply of raw materials in a traditional value chain. In many instances, no value at all is shared locally for exploiting biodiversity as a source of information, which leads to biopiracy. There has been some recognition of traditional knowledge rights in some of the international agreements such as the Nagoya protocol and in the World International Property Organization (interesting cases include patents related to the Neem Tree, see Marden, 1999), but practice difficulties remain reflect the contributions of inspiration from natural assets in intellectual property rights as further discussed in section 6.4.

Section 4 of this paper shows that the policy tools and institutions required for the functioning of nature-inspired innovation ecosystems has generally been lacking in developing countries, and that while the discussion on the economic value of biodiversity protection in developing countries has more often focused on activities around ecotourism, it as an insufficient alternative to the harmful exploitation in biodiverse region as it is not only volatile and environmentally dangerous, but it also does not lead to the creation of a sufficient amount of high-skilled jobs and spill overs to other sectors to sustain livelihoods.

4. NATURE-INSPIRED INNOVATION LANDSCAPE: UNEVEN DISTRIBUTION OF VALUE AND NORTHERN EXPLOITATION OF SOUTHERN BIODIVERSITY

Whilst the biomimicry sector is still in relatively early stages compared to its envisioned potential, several governmental initiatives have sprung up in the past two decades, mostly across North America, Western Europe and in some parts of East Asia. The nature-inspired innovation landscape has been dominated by a handful of advanced economies in the global north. As shown in Table 1, the leading countries in which governments have begun supporting biomimicry R&D through various programmes and grants are Germany, South Korea, the United States, as well as France and the UK to a lesser extent. Those findings echo the existing concern in Swanson (1997) regarding the substantial reliance of northern-based industries on southern-based biodiversity for R&D processes in various industries.

Table 1. Leading biomimicry-related policy initiatives across the World

Country	Key Public Agencies	Programme/Policy	Further details
France	Ministry of Ecological Transition Ministry of Agriculture & Foodstuff Economic, Social and Environmental Council	Centre Européen d'Excellence en Biomimétisme (CEEBIOS) Strategie Bioeconomie Pour La France, Plan d'Action 2018-2020	CEEBIOS launched in 2014 to coordinate academic research with over 200 laboratories and firms dedicated to biomimetics in France. Set up of biomimicry norms (optimisation and methodology)
Germany	Federal Ministry for Education and Research	BIOKON KompetenznetzBiomimetik	The Bionics Competence Network (BIOKON) hosts the 28 major players in the field of bionics and biomimetics in Germany and aims demonstrate the possibilities of bionics to business and industry, science, and the general public, and subsequently tap its full potential The German government has investment over 120 million euros in those networks since 2001
South Korea	National Government Ministry of Environment	Blue Technology Development Promotion Act to promote the development of biomimicry technologies through systematic governmental support	South Korea's Ministry of Environment has committed to invest 25 billion won (around USD20million) on biomimicry R&D projects between 2019 and 2023, to develop nature-inspired environmental pollution

	North Gyeongsang and South Jeolla provincial governments	Creation of various industrial clusters, councils, and industrialisation plans based on biomimicry	management systems, and to commercialise existing biomimicry technologies.
Switzerland		Inter-university centre (bringing together the university of Fribourg, EPFL and ETH Zurich) dedicated to bio-inspired materials.	This programme involved an investment of *EUR26 million.*
United Kingdom	UK Government	NIM (Nature Inspired Manufacturing (Previously known as BIONIS) Small Business Innovation Research (SBIR) program	The Biomimetics network for industrial sustainability (BIONIS) was set up in 2002, with the help of UK government funding to promote R&D and cooperation regarding biomimicry
United States	Department of Defence Department of Energy National Science Foundation	Bio-inspired Manufacturing (Small Business Innovation Research program) The Defense Advanced Research Projects Agency (DARPA) Advanced Research Projects Agency- Energy (ARPA-E) The Global Innovation through Science and Technology initiative	Funding of early stage technologies Identification of priority and strategic biomimicry R&D.

It is interesting to note that the development of biomimicry-related innovation in advanced economies has relied on proactive policy support. In the United States, the development of biomimicry has been spearheaded by several government agencies. For instance, the Pentagon's research and funding arm, the Defense Advanced Research Projects Agency (DARPA), has been the largest financial supporter of biomimicry research following the recognition that, if understood properly, biological strategies could inform new defense capabilities (Johnson, 2010; Kennedy et al. 2015). For instance, in a very direct application of biomimicry principles, DARPA has contributed $4 million to AeroVironment since 2006 to create a prototype "hummingbird-like" aircraft (which can move in three axes of motion) for the Nano Air Vehicle (NAV) program (Hennigan, 2011). DARPA has also funded the development of BigDog, a dynamically stable quadruped robot that can run over rough-terrains and carry heavy loads, which mimics quadruped mammal leg articulation (Kennedy et al. 2015). More recently, DARPA has also been funding research to learn from nature to design artificial intelligence frameworks.[7]

Germany is another leading country in biomimicry research, with over 100 public research institutions conducting biomimicry-related R&D, and two institutional research networks (*BIOKON and KompetenznetzBiomimetik).* The German government has invested over 120 million euros in those networks since 2001.

In France, Biomimicry has been identified as a key innovation area in the national ecologic transition strategy *(Stratégie nationale de transition écologique vers un développement durable 2015-2020).* The economic impact of the development of biomimicry on the GDP of just the Nouvelle-Aquitaine region has been estimated to EUR 575 million to EUR 3177 million, with the creation of 5 626 to 31 082 jobs (Vertigo, 2018). A pioneering research centre in biomimicry (the CEEBIOS) has been established in 2014, alongside the creation of higher education programmes in biomimicry (bringing together the disciplines of physics, biology, and chemistry). Over 175 research teams and 100 firms are now active in biomimicry research in various sectors, such as energy, construction, and cosmetics (Le Monde, 2018).

[7] For instance, the US military research funding department is looking to insects because, anatomically, they are very efficient creatures when it comes to energy and size, and they have a unique way with problem solving, which can be useful for computational strategies (Hinchliffe, 2019)

South Korea has also witnessed impressive developments in the field of biomimicry in the last decade. The country's Da Vinci Index increased 8 times between 2000 and 2019 (Bae et al., 2019; Kim et al., 2020). Today, South Korea (29%) has the world's second largest number of biomimicry technology patents after the United States (Lee, 2020). It is predicted that local biomimicry development (commonly referred to blue technology in the country) will create an economic value of approximately USD62 billion and 650,000 new jobs by 2035, and a further USD 382 billion and 2 million new jobs by 2050 (Kim et al., 2020). It is also predicted that biomimicry development could lead to significant environmental savings of up to USD1.22 billion and USD 3.74 billion by 2035 and 2050 respectively, through reductions of pollution, carbon dioxide emissions, as well as other environmental harms (Kim et al., 2020). Until 2019, most policies supporting R&D and commercialisation of biomimicry-based products were limited to regional, rather than national levels, led by local governments such as the North Gyeongsang and South Jeolla provinces (Lee, 2019; Kim, 2019).[8] The national orientation of biomimicry-related policies began in October 2019, with the proposal of the Blue Technology Development Promotion Act in the National Assembly to promote the development of biomimicry technologies through systematic governmental support (Na, 2019). This bill encourages national-level support for the R&D of biomimicry technologies, as well as the provision of education and skills required for the future development of the sector through the establishment of a national biomimicry research centre, biomimicry information management institution, research as well as a biomimicry technology impact assessment (Lee, 2020).[9]

The government of China has also recently embraced biomimicry as an innovation strategy, with a number of prominent institutes conducting research, all receiving governmental funding. Biomimicry has been included in the government's development strategy, especially related to design and architecture (Polites, 2019). There are also programmes and some funding for Circular Economy research programmes, as well as bionics, as part of a greener more innovation-oriented approach taken by the Chinese government.

While biomimicry has been increasingly identified as a strategic innovation sector and supported by a range of policy tools in a handful of advanced economies, its potential has been mostly overlooked in developing countries. Besides the existence of biodiversity museums such as in Brazil (Amazonia Science Museum) and Panama (Biodiversity Museum), intended to spread scientific value of forests and the importance of biomimicry, very few public policies have been designed to promote the domestic development of nature-inspired technological innovation, as later detailed in section 5.1.

5. PRELIMINARY ANALYSIS OF THE LATIN AMERICAN CONTEXT

Given Latin America's vast endemic biodiversity and unique natural ecosystems, biodiversity-inspired innovation can be a transformative force for the economic development of the region. Nevertheless, to date, most the initiatives related to biomimicry have been isolated and small in-scale given the lack of national coordination efforts and appropriate policy frameworks. This section provides a critique of the current discourse on biodiversity protection across Latin America and in Ecuador in particular, which has tended to narrow and un-developmental.

5.1 The Latin American context

[8] For instance, in 2015, the North Gyeongsang Province announced its plan to enhance research and commercialisation of nature-inspired products, and formed a "blue technology industrial cluster" as well as a "blue technology council" to achieve that objective (Lee, 2019). Similarly, in 2016, the South Jeolla Province introduced an outline of the blue technology industrialisation plan (Lee, 2020) with close cooperation with the Gwangju Institute of Science and Technology (GIST) (Kim, 2019).
[9] In a similar perspective, South Korea's Ministry of Environment has committed to invest 25 billion won (around USD20million) on biomimicry R&D projects between 2019 and 2023, to develop nature-inspired environmental pollution management systems, and to commercialise existing biomimicry technologies (Ministry of Environment, 2020).

The focus on Latin America is justified by the region's singular physical geography, which explains why it contains seven of the thirteen most biodiverse countries in the world, namely Brazil, Colombia, Mexico, Peru, Ecuador, Bolivia and Venezuela (see figure 4a). The interplay between the region's biodiversity and economic activity is a vitally important narrative in Latin America (Purkey, 2021). For many years, this interplay tipped in favour of resource extraction and use (ibid.). Nevertheless, the growing global focus on sustainable development and ecological sustainability increasingly prompts a discussion between the continued reliance on traditional extractive economic activity and the desire to preserve the region's unique natural treasures (ibid.) Against this backdrop, it is worth exploring the role of biomimicry as providing a sustainable economic alternative to deforestation and environmentally damaging extractive activities in the region. The natural biodiversity of the Latin American region has inspired several interesting inventions and innovations in the space and holds great promise in terms of potential and future innovations (see Annex 1). The localisation of biodiversity-inspired R&D in Latin America is further justified by the fact that many of the fauna and flora species are endemic to the region and not found elsewhere, as well as the fact that the transport of genetic resources is often restricted by legal frameworks anchored in the Nagoya Protocol on Access and Benefit Sharing (though this issue is further discussed in section 6.4).

It is also worth mentioning that the region has already witnessed efforts to capitalise on the innovation value of biodiversity through bioprospecting. The most well-known initiative took place in the 1990s in Costa Rica, with the creation of the National Biodiversity Institute (INBio) to conduct biological inventories, biodiversity prospecting, and management and distribution of Costa Rican biodiversity information (Zebich-Knos, 1997). INBio worked under the premise that a country will be able to conserve a major portion of its wild biodiversity if this biodiversity generates enough intellectual and economic benefits to make up for its maintenance (Mateo et al. 2001). However, questions have been raised regarding the relative economic benefits of bioprospecting, as illustrated with the deal between Inbio and the pharmaceutical company Merck, in which the royalties to be earned by Costa Rica should Merck develop a commercial drug are believed to be less than 5% (Hurlbut, 1994; Meyer, 1996; Campbell 2002). After almost three decades of activity, Inbio has effectively due to the dried-up funding sources and inability to become financially sustainable (as pointed out in personal interviews with various former and current policy makers in Costa Rica).

Despite its considerable potential, the biomimicry sector has so far been in rather nascent stages across Latin America and has received far less attention than bioprospecting. Two recent reports of the United Nations Economic Commission for Latin America and the Caribbean (CEPAL) have identified biomimicry amongst the possible bioeconomy development routes (Rodriguez, 2019; Gramkow, 2020). Nonetheless, these mentions remain very brief, and no study analysing biomimicry as an innovation strategy in Latin America has been conducted to date.

Across the countries surveyed only a few government policies exist, and entrepreneurship and research has so far been rather minimal as shown in Table 2. Governments in Mexico, Colombia and Chile have taken non-negligible steps in terms of both research and firm-level activity, while policy support for biomimicry activities is quasi-non-existent in countries such as Argentina, Brazil, Ecuador, Costa Rica, and Panama.

Table 2: Preliminary Mapping of Biomimicry research, initiatives, and policies in Latin America

Country	Biomimicry research/training programmes	Number of firms identified as of January 2021	Existence of government policies
Argentina	3 (UNL; UNRC; INTA)	1	No policy identified
Brazil	1 (INPA)	5	No policy identified, beside the set-up of the Amazonia Science Museum to "emphasize the importance of biomimicry".

Chile	4 (U. Aldofo Ibáñez; U. de Chile; U. Catolica; U. de Santiago).	3	*Explore Programme* as part of the National Commission for Science and Technology (CONICYT)
Colombia	1 (Universidad Pontificia Bolivariana)	4	Identification of biomimicry as a strategic sector by the Government but otherwise limited policy support.
Costa Rica	4 (U. de Costa Rica; Veritas University; Lanotech)	0	Public funding of programmes on Nano-Biodiversity and Nano-Biomimetics through the *Laboratorio Nacional de Nanotechnologia.*
Ecuador	3 (ESPE; U. Nacional de Loja; IKIAM).	1	No policy identified
Mexico	2 (UNAM; CICY)	5	The government has funded two key biomimetic research centres in the last 5 years (LaNSBioDyT; Biomimic Scientific and Technological Cluster).
Panama	2 (Geoversity; Universidad Tecnológica de Panama)	0	No policy identified
Peru	1 (Universidad de Ingeneria y Technologia)	0	No policy identified

Brazil, despite being the most biodiverse country in the world, has particularly lagged behind in terms of building up a biomimicry ecosystem, which can be partially explained by the economic downturn of previous years, which led to many organisations cutting R&D capabilities and a lack of governmental investment in biomimicry programmes (Voce A/S, 2019) Biomimetics is also area of huge potential for Chile given its diverse ecosystem and number of endemic species. For example, over 62% of Chile's marine species are endemic to the country and not found elsewhere (Conicyt, 2016). Nevertheless, the sector is at an early stage in Chile, although some research, companies and state-sponsored programmes do exist. To further understand opportunities and obstacles in promoting biomimicry in Latin America, the next section provides a deeper analysis of the country-level contexts of Costa Rica and Ecuador.

5.2 Successes and failures to leverage the innovation value of biodiversity in Costa Rica and Ecuador

5.2.1 Biodiversity-based development and the limits of the sole reliance on ecotourism

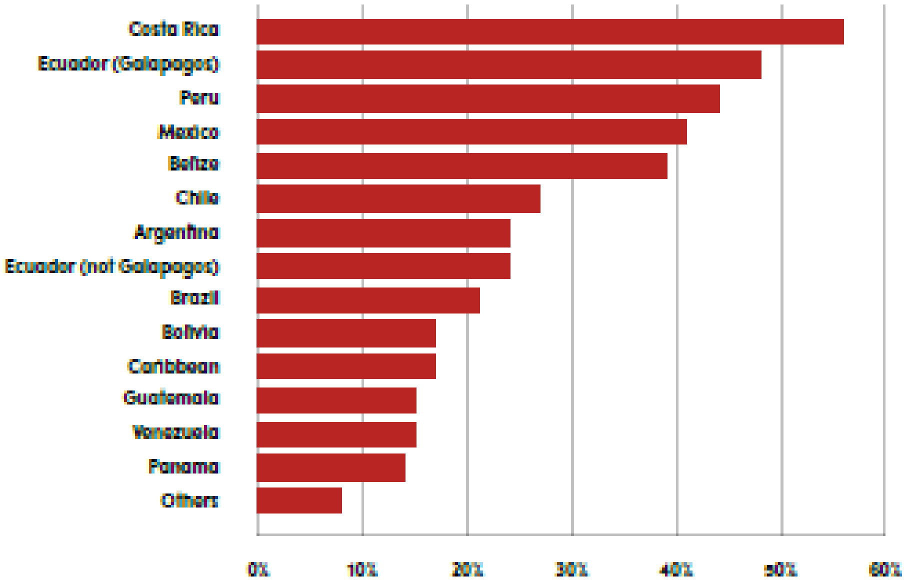
Both Costa Rica and Ecuador are considered amongst the most biodiverse countries in the world, despite their small land surface (UNDP, 2020). Biodiversity has therefore been a central issue in the development policy debate in both countries. However, though Costa Rica has pioneered policy efforts to leverage the economic value of biodiversity, with the clear recognition of the need to find ways to generate value from nature as an asset through innovation (Minister of Environment of Costa Rica, Personal Communication, 17 November 2021), the policy debates on biodiversity protection in Ecuador have tended to be narrower in terms of the ways in which the country's unique biodiversity could be leveraged as a lever for development. The existing policy discourse in Ecuador is dominated by an unproductive dichotomy between environmental preservation and exploitation. Such dynamics are well reflected by the Yasuní-ITT Initiative, which directly confronted the issue of leaving oil in the ground in the Yasuní National Park, one of the most biodiverse hotspots in the world, which failed due to the lack of international coordination to compensate for biodiversity protection from which the whole world benefits[10], unclear legal frameworks, but also the lack of concrete developmental alternatives to oil exploitation and utilisation of biodiversity as a more sustainable source of revenues beyond ecotourism.[11]

[10] See Gatti et al. (2010) for a discussion of the failure to recognise the contributions of the South to the production of cooperative surplus

[11] The initial proposal by the Government of Ecuador involved keeping almost a billion barrels of petroleum underground if the international community contributed with at least half of the opportunity cost of exploiting the petroleum (Larrea and Warnars 2009). The initial support from international institutions, European governments, and NGOs worldwide did not translate into concrete action and the

Ecotourism has become increasing popular across Latin America as a way to promote environmentally friendly growth, (see Figure 5). Ecotourism's appeal rests in its potential to provide local economic benefits while maintaining ecological resource integrity through low-impact, non-consumptive resource use (Stem et al. 2003). Both Costa Rica and Ecuador (in the Galapagos Islands more particularly) are amongst the major ecotourism destinations in the world (see figure 5). Nevertheless, overreliance on ecotourism has often posed important environmental and developmental risks (Purkey, 2021). Ecotourism's risks reveal the importance of identifying alternative ways to capture the economic value of biodiversity conservation to complement -and at times supplement- ecotourism, which cannot be viewed as a benign, non-consumptive use of natural resources in biodiverse nations (Jacobson and Lopez, 1994).

Figure 5: Percentage of US-based ecotourism operators offering products by country.



Source: Purkey, 2021

The risks associated with dependence on ecotourism is demonstrated by the experience of the emblematic Galapagos Islands, which have become overdependent on tourism as a source of funding for biodiversity protection. The problems associated with ecotourism were threefold:

1. *Environmentally damaging*: In 2007, due to the uncontrolled development of tourism, the Galapagos were even included in the Danger List of the UNESCO World Heritage Sites.
2. *Lack of value added and knowledge spillovers:* It is highly unlikely that ecotourism can generate sufficient skilled jobs to act as an engine of growth and therefore a sufficiently attractive alternative to biodiversity exploitation/extractive activities.
3. *Revenue Volatility:* Revenues from tourism are highly vulnerable to external shocks, as demonstrated by the COVID crisis. The monthly number of tourists visiting the islands dropped from 25,000 to 6000 in the post-pandemic period, which represents a drop of 75% between 2019 and 2020. While nature has gained some relief, the issue is that the revenue dropped have deeply impacted the local economy and livelihoods, as well as the public budget to maintain local natural ecosystems.

As a result of those factors, the local government of the Galapagos Islands is attempting to develop research and innovation activities to replace tourism as the main sources of local livelihoods and funding for biodiversity protection (Norman Wray, Governor of the Galapagos

2008/9 financial crisis also added pressure on Ecuador's international sources of financing, which led President Correa to pursue his backup plan to drill for oil if contributions were not received (ibid.). In that perspective, despite its failure, several lessons can be learnt for the future success of similar programmes.

Islands, personal interview, April 2021). While 85% of the Galapagos Economic activity used to depend directly or indirect on tourism before the pandemic, “it has become essential to recover economic activity in a way that is productive, inclusive, resilience, and environment-friendly” (Luis Felipe López-Calva, UNDP director for Latin America, cited in UN 2020). Holding the second marine reserve of the World, the Galapagos Islands are often referred to as a ‘the largest live biodiversity laboratory of the world’ and have famously inspired Charles Darwin’s evolution theory, which shows the value its local ecosystems hold as a source of information. However, such potential has been mostly unfulfilled to date given the limited local R&D capabilities to conduct biomimicry activities, such as the lack of specialised local universities (the only higher education institution being an extension of the USFQ which provides mostly non-technical courses). As a result, local populations have struggled to gain the required skills for the development of a local nature-inspired innovation ecosystem. [12] As a first step towards a new innovation-based development model, an innovation hub was created in May 2021 under Ecuadorian law to attempt to mitigate some of the challenges by generating income from research and innovation. This innovation hub is the first public policy aiming to promote innovation activities in the Galapagos. (Norway Wray, Governor of the Galapagos Islands, personal interview, April 2021). Though bio-innovation does not ensure conversation, and the impact this initiative will have on the long-term conservation efforts is not clear yet, it represents a promising step forward because of its identification of synergies between biodiversity and innovation, as well as its orientation as a potential alternative source of financing for conservation.

In Costa Rica, eco-tourism has also gained appeal as a strategy to align both conservation and development, and assessments of its impact in the country have been mixed (some negative impacts raised in the literature include solid waste generation, air pollution, habitat destruction, and sociocultural ills; see Jacobson and. Lopez. 1994; Stem et al. 2003; Koens et al. 2009 for instance). In their study of the effectiveness of ecotourism as a conservation and development tool in Costa Rica, Stem et al. (2003) find that scale influences tourism's benefits and negative impacts and that, where ecotourism dominates local economies, towns may become economically vulnerable. Ecotourism is most effective as a component of a broader conservation strategy and if embedded in a broader process of capacity building. In that sense, Costa Rica has taken important steps in that direction. For instance, since the 1990s, Costa Rica’s Payments for Environmental Services Program (PES) is a financial mechanism whereby landowners receive direct payments for the ecological services which their lands produce when they adopt land uses and forest management techniques that do not have negative impacts on the environment and which maintain people's life quality (Malavasi and Kellenberg 2002). Costa Rica's Forest Law (adopted in 1996) recognizes four environmental services provided by forest ecosystems: (i) mitigation of GHG emissions; (ii) hydrological services, including provision of water for human consumption, irrigation, and energy production; (iii) biodiversity conservation; and (iv) provision of scenic beauty for recreation and ecotourism. In contrast to Ecuador, ecotourism in Costa Rica has indeed been embedded in a national vision for leveraging the economic value of nature, and the government has historically shown greater ambition efforts to leverage the economic and innovation value of biodiversity (although almost entirely restricted to bioprospecting), as discussed in the next section.

[12] Interviews with local stakeholders also identified the low internet connectivity as an obstacle to the development of innovation activities in the island (a future plan to install fibre optic cables in 2022 is expected to increase the connectivity of the islands).

5.2.2 Isolated biomimicry-related initiatives in the context of limited state support

The potential development of biomimicry activities in both Costa Rica and Ecuador is considerable because of the existence of large shares of the world's endemic biodiversity, but also the existence of related frontier research capabilities domestically, such as the mapping and discovery of new species, which often involved partnerships between local and foreign research teams through shared projects.[13] Nevertheless, as further discussed below, very few universities provide technical training related to biomimicry in order to translate local capabilities in biological mapping into technological innovations, (with the exception of the Yachay programme in Ecuador, which is anticipated to include education and research on bio-inspired topics, amongst many other fields, and the existence of bioengineering and nanobiotechnology programmes in the Universidad Nacional and CeNAT in Costa Rica). In addition, although bioprospecting activities have been scaled up since the 1990s in Costa Rica, in Ecuador "less than 10% of the country's biological diversity has been inventoried, let alone studied" (Luis Coloma, director of the Jambatu Amphibian Research Centre, cited in Bellota, 2016), which is why Ecuador's government has a key role to support large-scale projects with universities and research centres to complete the inventory of biodiversity in the country.

Notwithstanding Ecuador's considerable potential for nature-based technological innovation, the persistence of market and institutional obstacles remain key challenges to be addressed. No specific policy related to biomimicry has been identified in Ecuador public policy support for biomimicry is quasi non-existent. As a result, most biomimicry activities conducted in the coutnry appear to be university spinoffs that have not managed to scale up due to the lack of available funding and high cost of laboratory operations. For instance, Anuka is a firm that takes advantage of the capacities of endemic microalgae of Ecuador, adapting them in to reduce the presence of CO_2 in the environment. The advantage of this type of volcanic algae that exists in Ecuador is that it offers more resistance to bacteria and to fungus than most microalgae found around the globe. Interviews with this local firm operating in the biomimicry-based innovation sector further confirm that because of the lack of university programmes that provide biomimicry training, some of the team of researchers had to enrol in a second postgraduate degree in nanotechnology to complement their initial training in applied bioscience, at their own cost of time and financial resources. Anuka has later developed as a university-spinoff after winning a USD 10,000 prize from the Inter-American Development Bank, which enabled the firm to create a laboratory.[14] However, the growth of the firm and the development of the commercial phase was stunted by the lack of domestically available non-repayable funding, as well as the high costs of operating laboratory in Ecuador (due to the need to import laboratory equipment that is not locally available). The existence of high interest rates (which are even higher than consumption credits) also prevented the firm from securing loans from the domestic banking sector. Despite fulfilling its eligibility conditions, the firm was also denied funding from a government program, the 'Ideas Bank' (*Banco de Ideas*), which is part of the Secretariat for Higher Education, Science, Technology and Innovation, on the ground that the field of operations was not deemed strategic by the government (ANUKA's CEO, Personal communication, April 2021). Due to the lack of domestically available cheap and non-repayable sources of seed funding, the firm has considered moving its operations to Spain, where the availability of laboratory equipment and prospective larger contracts for the installation of biofilters for the municipality of Madrid offers better perspectives for scaling up.

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[13] The need for foreign firms and researchers to collaborate with local researchers is notably due to restrictions in the access to local genetic material and permits required from the Ministry of Environment, as well as the fact that local teams often have better knowledge of the local natural ecosystem.

[14] The firm later won several international awards and successful applied to other international sources of funding (such as Startup Chile and The Global Innovation through Science and Technology initiative, which is a U.S. government program).

Costa Rica has shown far greater policy initiatives towards capturing the economic value of biodiversity, though the efforts towards the capturing the country's biomimicry potential more specifically have been very limited. Costa Rica's flagship initiative to promote the innovation value of biodiversity, the National Biodiversity Institute (INBio), was created in the 1990s to conduct biological inventories, biodiversity prospecting, and management and distribution of Costa Rican biodiversity information. INBio led to the commercialisation of three products, but, as mentioned in section 5.1, after almost three decades of activity, it has ceased to operate due to the dried-up funding sources – 80% of which came from the international community- and inability to become financially sustainable (Personal Communication, Former Minister of Environment of Costa Rica, November 2021). More recently, under the Alvarado-Quesada government and in the context of the recovery from the COVID crisis, several key initiatives to promote bio-innovation were launched. Those include:

- The National Bioeconomy strategy, launched in 2020, to promote a green knowledge economy.
- The Biomaterials hub, funded by the IDB Lab and promoted by CINDE, Costa Rica's investment promotion agency, to promote R&D around biodiversity and biosustainability for domestic firms that do not have R&D capabilities.
- The BioAlfa project, which was formally launched by a Presidential Decree in 2019, to generate precise mapping and identification of every specie in Costa Rica through DNA barcoding, or molecular analysis, before placing this information in an open-source, publicly available database.

Those efforts remain largely focused on utilising natural assets as a source of genetic material rather than a source of inspiration for innovation, which imply two different research processes (see Figure 1). Meanwhile, no biomimicry initiatives have been identified in the country besides four university-level research projects currently undertaken at the Universidad de Costa Rica, LANOTECH, Veritas and Universidad Nacional.[15] Nevertheless, none of these projects have evolved into businesses (as in the case of Anuka in Ecuador).

In both Costa Rica and Ecuador, the interviews with a range of stakeholders pointed to several bottlenecks that are common across both countries and that have hindered the development of biomimicry activities and their commercialisation:

- Lack of awareness regarding biomimicry and its potential
- Lack of a critical mass of specialized human capital due to lacking interdisciplinary university training related to biomimicry
- Weak academia-industry linkages and coordination between stakeholders for R&D
- Administrative hurdles and difficulty to obtain permits to conduct research using the nation's biodiversity.[16]
- Limited funding available to pursue biomimicry R&D

Resolving these coordination failures that are stunting the growth of biomimicry activities requires the strategic use of policy interventions. For instance, the provision of funding, facilitation of access to study biodiversity and the promotion of integral and interdisciplinary education programmes in biomimicry processes will be crucial for the successful development of local nature-inspired innovation ecosystems. The policy implications of these findings are discussed in the next section.

[15] The researchers leading these projects study the cooling properties of long-horned beetles; the adhesive properties of hydrogel secreted by a specie of worms; and antibacterial properties of pineapple peel (Personal communications with lead researchers; October/November 2021).
[16] In Costa Rica, almost every researcher interviewed as part of this study (over 20 researchers) have complained about the administrative hurdles posed by CONAGEBIO to handle genetic material for research.

6. POLICY AND THEORETICAL IMPLICATIONS

6.1 The role of state interventions to catalyse biomimicry innovation ecosytems

This preliminary analysis of the global nature-inspired innovation landscape and the Latin American context leads to several findings on the type of coordination failures that hinder the development of nature-inspired technological innovation, and on the need for a systemic policy approach, in line with the vast literature on national innovation ecosystems which highlight the role public institutions for R&D support, technological incubation, transfer and diffusion (Lee, 2013; Lundvall, 2010; Malerba, 2002; Nelson and Winter, 1982).

Government interventions that have enabled the successful development of biomimicry-related activities in leading countries have gone far beyond fixing market and instead are shaping the accumulation of productive capabilities. In contrast to static approaches to comparative advantage, which are path dependent upon established capabilities, dynamic approaches to comparative advantage, which acknowledge the role of policy for technological upgrading, learning by doing and capabilities accumulation (e.g Dosi, 1982; Katz, 1984; Nelson and Winter, 1982; Lall, 1992; Chang, 2013; Mazzucato, 2016; Lebdioui, 2019), view innovation as dependent upon the generation of feasible new capabilities. Hence, in line with Schumpeterian perspectives, to catch up, developing countries must create new value-generating activities as a means of searching for higher profits and employment from innovation, as opposed to statically maximise rents from an existing income stream. Those dynamic perspectives can help explain the transitions towards knowledge intensive activities beyond mere resource exploitation skewed towards raw material exports. It is in such dynamic perspective that the process of biomimicry-based innovation in latecomers as well as the role of state interventions to alleviate the lack of pre-existing innovation capabilities can be explained.

Biomimicry can involve both strategic and serendipitous innovation. For instance, as mentioned earlier, the biomimicry promoted in the United States by the Department of Defence is looking directly at specific species (such as insects or the hummingbird) to help achieve specific innovation objectives (computational strategies in warfare and new generation drones), while in contrast, it is while taking a walk through the woods that Swiss electrical engineer, George de Mestral, discovered the cocklebur is comprised of hundreds of tiny hooks that cling tenaciously to fabrics and animal fur, which inspired the invention of Velcro. There are consequently two main ways in which nature-inspired innovations can take place: a strategic/targeted approach, and a serendipitous/scouting approach.

1) ***Strategic / Targeted approach***: this approach entails looking to nature to help address an already identified problem. It relies on some pre-existing understanding of our natural ecosystem and solutions it could offers, and the identification of specific species or natural phenomena that solves given challenge. (e.g. research on the hummingbird's morphology for flying backwards; or photosynthesis for carbon capture).

2) ***Serendipitous / Scouting Approach:*** this approach entails a general scouting for ideas by looking at nature. Sometimes the problem is not identifying until a better solution is provided. While organizations invest heavily in systematic strategies to accelerate innovation, historical analysis and individual experience also suggest that serendipity plays a significant role in innovation (Fink et al.2017). This approach however also relies on pre-existing engineering and design knowledge, as to enable agents and firms to recognise useful solutions in nature when they see them (in other words, they 'know when they see it', similarly to Velcro's founder with cocklebur).

National innovation ecosystems around biomimicry consequently need to be built to foster both strategic and serendipitous innovation. Such innovation ecosystems can help organizations invest heavily in systematic strategies to accelerate innovation, but also lay the ground for allowing agents and firms more exposure and opportunities for serendipitous innovation. This could be done by more systematically considering nature when trying to solve engineering problems, and raising awareness regarding the usefulness of biomimicry as a research process. The creation of 'eco-labs' in biodiverse areas, where the natural ecosystem is preserved, and researchers and firms are invited to explore and investigate the usefulness of various species for existing challenges, could also help promote and incentivise serendipitous innovations through biomimicry.

6.2. Public Financing: Patient and non-repayable R&D funding

Public financing is critical to low carbon transitions and in the process towards a more sustainable social and economic model. Several authors have already shown that the state had a key role to play in past energy transitions. Semeniuk and Mazzucato (2018) show that public financing was central in national energy transitions, such as in Iceland (from fossil to geothermal energy), Norway (to hydroelectricity), France (from oil to nuclear) and the United States (from conventional to shale gas).

The key role of public financing lies in the fact that the availability of long-term, patient, and non-repayable R&D funding is essential to stimulate the early stage development of low-carbon technologies, especially when profits from innovation can only be expected far into the future (Anzolin and Lebdioui, 2021; Mazzucato 2013a, 2013b, 2016). However, in the absence of a functional national development bank tasked with the mission of funding structural transformation towards higher value-added activities, the domestic private banking sector, especially in developing countries, tends to be risk averse and often fails to provide the conditions that enables long term and patient seed funding for new innovations, as shown in the case of Ecuador in this paper.

The firm-level case of Anuka presented earlier in this paper, reveals the consequences of the lack of non-repayable seed funding, which is the stunted growth of the commercial phase and the eventual delocalisation to countries where conditions are more favourable to entrepreneurs. As a result, the argument that more (not less) public interventions are needed to transition to a low carbon economy is also evidenced in the context of the development of biomimicry-based innovation.

6.3. Education policy for nurturing biophilia and targeted human capital

The state has a key role to play as a catalyst of targeted human capital accumulation required for the development of new sectors, especially in countries with little pre-existing related capabilities (Gerschenkron 1962; Lebdioui, 2019, 2020). The development of biomimicry activities makes the role of education policy even more relevant because unlike many other 'traditional' sectors, it requires a strategy mix of skills (such as biology, chemistry, and engineering skills) which the standard curriculums does not provide. Biomimicry design processes rely heavily on biological knowledge, but also on design and engineering, especially when it comes to abstracting biological strategies into more broadly applicable design principles and implementing them to solve human challenges (Kennedy et al. 2015).

Such human capital dynamics are visible in the countries that have accumulated frontier R&D capabilities in biomimicry. For instance, in Germany, there are over 15 undergraduate and postgraduate degrees related to biomimicry, out of a total of 25 in Europe. In France, CEEBIOS involved 175 biomimicry research teams by 2019 (against 45 in 2012) but no degree courses. In other to remedy this gap, two higher education institutions have created in 2020 pioneering courses dedicated to biomimicry (the *Ecole nationale supérieure de création industrielle* - ENSCI, and the *Université de Pau et des pays de l'Adour*). Such courses "will finally put an end to this teaching in silos, which isolates biologists from physicists, chemists and mathematicians" (codirector of the future master's degree in bio-inspired materials of the University of Pau, Interview cited in Le Neve, 2019).

Besides the introduction of higher education programmes related to biomimicry, the role of primary and secondary education is also key due to the importance of biophilia in stimulating interest in biomimicry processes. Biophilia is a term coined by Edward O. Wilson and can be defined as a human tendency to interact and associate with other forms of life in nature. It is a tendency that can get induced and developed from a young age, which sheds light on the role for primary and secondary education to inculcate an appreciation of biodiversity in terms of both its ecological and innovation value. In Ecuador, most people who have access to university engineering/R&D skills do not tend to have a deep engagement with/appreciation of nature (notably due to a urban/rural and class divide), while people who display biophilic behaviour usually do not have access to the scientific skills and capabilities enabling them to engage in technological innovation (CEO of Anuka; Personal Communication; April 2021). There is also a social dimension of inclusion of indigenous communities and knowledge into R&D processes. Improving access to STEM field for indigenous communities that tend to display biophilic behaviour is also key for the development of an inclusive and green model of innovation and development.

The promotion of biomimicry therefore requires a collaborative framework between various actors, such as governments, education providers, and research units. Such collaboration is necessary to tackle skills mismatches and provide new skills required to shape the dynamic innovation-driven processes taking place around biodiversity.

6.4. Revisiting legal frameworks for benefit-sharing

Even though environmental assets have considerable value as sources of information that feed into research, innovation, and industrial processes, the benefits from nature-inspired innovation have often failed to compensate for such value. The essential role of biodiversity as an informational input into fundamental industries highlights the importance of developing mechanisms for recognising this role and its value to those who invest in its retention, similarly to the ways in which human-based sources of information are compensated for through intellectual property rights (Juma, 1989; Swanson, 1997).

The institutional and property rights concerning the extraction of genetic material and local knowledge are well known (see Correa, 2011; Gupta, 2004; Von Lewinski, 2008) but the issue of biomimicry makes this problem worse, as it is more difficult make claims of ownership or compensation for engineered solutions that mimic biodiversity than it is to make an intellectual property claim about a life science solution synthesised from natural organisms. This is because innovators and firms do not need to declare where they have dawned inspiration from, and it is more difficult -and not necessarily desirable- to restrict the process of inspiration – rather than extraction- from solutions that are available in nature as a public domain.[17]

Another issue is that extracting – or getting inspiration from- genetic resources does not require foreign direct investment or the purchase of exploration permits (as in the case of extractive resources). As a result, the use of biodiversity as informational input for R&D has often led to biopiracy - is practice in which the local knowledge of nature is used by others for profit without authorization or compensation - as demonstrated in this study.

Notwithstanding the considerable difficulties in monetizing the value of environmental assets as a source of inspiration, ensuring rightful compensation requires the existence and enforcement of national and international legal frameworks. Such objectives were a central part of the Nagoya Protocol on Access and Benefit Sharing (ABS), which is a 2010 supplementary agreement to the 1992 Convention on Biological Diversity (CBD) (preceding the 2021 Kunming Declaration which calls for further action for biodiversity protection). Its aim was the implementation of the fair and equitable sharing of benefits arising out of the utilization of genetic resources (which includes R&D as well as subsequent applications and commercialization based on those resources) with the contracting party providing genetic resources, thereby contributing to the conservation and sustainable use of biodiversity. Nevertheless, this protocol has not always been respected. Furthermore, the United States has yet to ratify its participation in the CBD and has not even

[17] The role of vision and intuition tend to be under-reported: a study of 33 major discoveries in biochemistry “in which serendipity played a crucial role” concluded that “when it comes to ‘chance’ factors, few scientists ‘tell it like it was’ (Tria et al. 2014).

signed the Nagoya Protocol (while countries such as Australia, France and Japan have signed but not ratified it yet).

The concept of benefit-sharing is also key to the connection between biomimicry and conservation. In principle, although biomimicry relies on the availability – and by extension conversation- of natural assets (a biodiversity stock), the two processes do not need to be mutually re-enforcing. To associate the practice of biomimicry with a conversation agenda, appropriate legal frameworks and institutions are needed to back up resources for biomimicry with protected area status and protection of the biodiversity stock. This is particularly important in the context of serendipitous innovations, where there is uncertainty about how useful the organisms are from an R&D perspective, and their usefulness may only arise in the future. Given that a country's biodiversity stock can be a knowledge bank of solutions to unknown problems of the future. different mechanisms are required to renumerate and protect these potential sources of innovation value. In that sense, the experiences of some countries (such as Costa Rica) with bioprospecting can hold important sources of lessons that can be adapted and applied in the context of biomimicry.

7. CONCLUDING REMARKS

In the context of an urgent need for a greener structural transformation and the emergence of development models that allow for better biodiversity protection frameworks, this paper has shown that biomimicry represents a promising avenue for latecomers well-endowed with biodiversity to leapfrog to the innovation frontier by leveraging their biodiversity as a stock of information for R&D process. This paper therefore builds on evolutionary and developmentalist perspectives, according to which developing countries must create new value-generating activities as a means of searching for higher profits and employment from innovation to catch up, as opposed to statically maximise rents from an existing income stream.

To date, the landscape for nature-inspired innovation has been dominated by advanced economies that have relied on proactive policy interventions, while virtually no developing country has adopted biomimicry as an innovation strategy. By drawing on the case of Latin American countries, this paper shows that the lack of policy and institutional support has led to the persistence of important coordination failures that has hindered the integration of domestic firms at the natured-inspired innovation frontier. A major rethinking of public policies towards supporting nature-inspired innovation ecosystem is therefore necessary,

The findings of this research have great potential for contributing to the current policy debates in various biodiverse countries. Nevertheless, several areas for further research are needed to fully understand the developmental dynamics of biomimicry in developing nations. For instance, in light of the lack of compliance with the Nagoya protocol, further research is needed to analyse the type of mechanisms that can be realistically implemented for benefit sharing and compensation for those who invest in preserving biodiversity from which important genetic materials and information is extracted.

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