THE IRREPLACEABILITY OF TROPICAL PRIMARY FORESTS

INTRODUCTION

Primary tropical forests provide a range of highly valuable ecosystem services that are of global significance for climate change mitigation and adaptation and biodiversity conservation [1,2]. Evolutionary processes over millennia have resulted in a level of complexity and stability that makes these forests irreplaceable and investing in their protection is critical to addressing humanity's gravest challenges [3,4]. Primary tropical forests maintain a very high level of ecosystem integrity and, as a result, generate superior ecosystem services, particularly, for example, the significant quantity of carbon stored in their biomass and soil [1]. These forests both sequester and store more carbon and store it more securely than other forests and offer far greater biodiversity benefits [2,3]. Protecting primary tropical forests will contribute most significantly to meeting international climate, biodiversity, and sustainable development goals [1,5].

Yet their ecosystem services are chronically undervalued and thus the forests are over-exploited. Society highly prizes individual components that make up a forest, such as its timber, or alternative uses of forested land, and conversely undervalues the myriad ecosystem services provided by the inherent complexity of that same ecologically intact forest [6]. As a result, the economic value generated by the sale of harvested timber, or the clearing of that forest for commodity production—activities that are bought and sold in a market and fetch a price—take precedence over protection, despite evidence the aggregated benefits provided by forests *in situ* outweighs the market value of timber [2,7].

These values are often fully understood by the people who live in, and are the custodians and stewards of, these forests, as to them their value resides in maintaining the ecological integrity of forests [8]. Increasingly, the role of forest stewards and Indigenous People is being recognised for both their contributions to local forest protection and to tackling global challenges, including mitigating climate change and biodiversity loss [4,5]. However, even this contribution is being eroded as complex webs of industrial development, organised crime, international trade in commodities, and unsupportive government policy encroaches upon the forest [11–13].

Primary tropical forests are at a critical juncture. The planet had already lost ~35% of its preagricultural forest by 2018 [14]; and the tropics lost 6.7 million hectares (ha) of primary forest in 2024; and this is increasing year-on-year [15,16]. After progress in reducing deforestation in the 1990s and 2000s, rates have again reaccelerated as conservation efforts are being reframed as barriers to rebalancing historic inequities in decolonised nations that wish to benefit from natural resource development opportunities [17–19]. Long established threats have reemerged as extractive enterprises intensify and exploit growing demand for agricultural commodities, new technologies drive demand for rare earth commodities, and climate change driven droughts and worsening wildfires impact otherwise highly fire-resistant forests [20,21].

There is some good news. Today, we have better information than ever on primary tropical forests and the value of many essential and irreplaceable attributes. We also have much greater clarity on the range of threats, from the expansion and intensification of industrial land use to road building, which lead to forest loss and degradation. We also have evidence of the capacities and resources needed to protect primary forests [19]. And countries are increasingly protecting their forests of ecological significance [22].

WHAT ARE PRIMARY FORESTS

The world's major primary tropical forest regions are in the Amazon basin, MesoAmerica, the Congo River Basin, and in New Guinea and Indonesia. Around 57% of global primary forests are in the wet tropical biome and 60% of this is in Brazil alone, underscoring the importance of engaging key host countries in international policy setting. Smaller, but nevertheless globally significant areas are found in Melanesia, Australia, the Sundaland, Indo-Burma, Mesoamerica, and the Guinean Forests of West Africa.

Primary forests are characterised as being *naturally regenerative* forests of *native tree species* that have *no clearly visible indications of direct human activities*, and whose *composition, structure and dynamics are dominated by ecological and evolutionary processes* [23]. The high level of ecosystem integrity that characterises primary forest is indicative of the forest being entirely self-organizing and self-regenerating [10]. As such, forests have a high level of stability, measured by the ecosystem's ability to resist external perturbation, resilience enabling it to bounce back after disturbance, and persistence over very long timescales. Primary forests are also characterised by their 'intactness' – the absence of industrial land use, industrial extractive activity, roads, hydropower, and other capital-intensive works, which fragment and degrade primary forests. An 'intact forest landscape' describes a very extensive (≥50,000 ha) unbroken expanse of natural ecosystems [24].

ECONOMIC VALUE OF ECOSYSTEM SERVICES

Primary tropical forests generate very significant ecosystem services. Ecosystem services are typically functionally categorised as (1) provisioning, (2) regulating, and (3) cultural, which are, in turn, all underpinned by supporting biochemical and physical processes, known as 'supporting' services. This categorisation has been systematised by the Common International Classification of Ecosystem Services (CICES) v5.2 [25], which is now adopted by the United Nations' System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) framework as the international standard for environmental stocks and ecosystem service accounting [26,27].

Ecosystem services can have economic values. This value is based on the concept of a subjective measure of 'utility' – its usefulness in achieving a goal for someone. Therefore, the economic value of the ecosystem services provided by primary tropical forests is based on their usefulness in achieving economic outcomes, such as improvements in societal wellbeing, which can include people's livelihoods and other material needs. Therefore, value, in this framing, is based on a relative value of the services provided by ecosystems when compared to the value an individual might attach to their own labour, recreation, shelter, sustenance, or health. *Monetary* valuation is a sub-set of economic valuation and ascertains someone's willingness to pay (WTP) for environmental improvements, or through their willingness to accept (WTA) compensation for environmental losses [28]. Thus, it allows for ready comparison with services commonly exchanged in markets, or the monetary valuation of

natural capital can enable comparison with other forms of capital stocks.

Whilst the quantity and robustness of monetary valuation studies is increasing, it still remains relatively costly to undertake primary valuation studies [2]. As a result, a range of data depositories and meta-analyses studies are becoming available to enable analysts to undertake 'benefit transfer' – estimating the monetary value of ecosystem services at a target site that is based on valuation studies from sites with similar ecosystem and socio-economic attributes. This includes the Ecosystem Services Valuation Database (ESVD) [29] maintained by environmental economists who worked on the original database of ecosystem service valuations established The Economics of the Environment and Biodiversity [30].

ECONOMIC VALUE OF PRIMARY TROPICAL FOREST ECOSYSTEM SERVICES

The high levels of ecosystem integrity and significant intact extent of primary tropical forests enable them to generate very significant quantities of high-quality ecosystem service economic values. Several are considered here.

Carbon removals and retention

Primary tropical forests are the biosphere's singularly most important stores of terrestrial carbon. Furthermore, once a forest reaches a primary condition it continues to absorb carbon for centuries [23]. Thus, from an economic perspective, primary tropical forests can be seen as providing both a store of value (an asset) and a flow of services. As such, they play a dual role in maintaining future climate stability [31]; both forms of carbon accounting are supported by the SEEA EA. The carbon stock in the living biomass of primary tropical forests amounts to an estimated 114 gigatonnes (Gt) of carbon, or 418 Gt of Carbon Dioxide equivalent (CO_2-e). Furthermore, this stock of carbon protected in primary tropical forests is highly stable and resilient to environmental and climatic change, which significantly reduce risks of leakage from investments in their protection.

Estimating the economic value of carbon retention and removal resulting from forest conservation is done in a range of ways. One approach estimates *future avoided damages* that will result from further emissions. Such cost-based approaches to value can also be used to generate an ecosystem asset value (i.e. the worth of a stable climate to human society). An important cost-based method is the 'social cost of carbon' (SCC), which is an estimate of the economic damage associated with each additional tonne (T) of CO_2-e emissions. It is quantified by assessing the long-term impacts of emissions on the global economy, including changes in net agricultural productivity, human health, property damages from increased flood risk, and ecosystem services and attempts to capture the full range of impacts, including both market and non-market. A review of country-based estimates of the SCC by Ricke et al. [32] revealed a median of global value of 417 US$/T of CO_2-e (low: 177 US$; high: 805 US$). Given DellaSella et al.'s [1] estimates on the quantity of carbon stored in tropical forests at around 482 Gt, with 159 Gt primary tropical forests, plus ongoing sequestration rates of 1.3 Gt yr^{-1} (equivalent to 13% of annual global anthropogenic CO_2 emissions [6]) this represents an annual flow of benefit of US$ 612 billion (the size of the Swedish economy) and a carbon asset valued at US$ 174.3 trillion and rising – today more than one hundred times the value of the Norwegian sovereign wealth fund.

This carbon asset is commonly customarily owned and managed by Indigenous People; around 36% of intact forest biomes are within Indigenous Peoples' land [8]. From this more local perspective, the economic value of carbon provides opportunities to access the burgeoning markets, funding, and investment schemes for carbon, such as the proposed Tropical Forest Forever Facility [i] and innovative payment for ecosystem services (PES) schemes [33].

Watershed services

Forests capture, store, and regulate the release of rainwater, which plays a critical role in generating ecosystem services. These include reducing downstream flooding, lowering risks to downstream food production, infrastructure and communities, regulating levels of the water table by improving water infiltration, preventing erosion, and assuring a high-quality water supply for aquatic species and people, industry, and agriculture further downstream [34,35]. Primary tropical forests have a significantly greater capacity for these services [36]. As the planet heats these forests will play an ever-stronger role in regulating more extreme regional droughts and floods and ensuring downstream water security for both ecological and economical functions, including drinking water for hundreds of millions of people.

Water related ecosystem services have been the subject of numerous monetary valuation studies [34] and have been demonstrated to generate very significant economic value in terms of wild food, flood mitigation services, saving billions of dollars in flood mitigation works, and by providing water security by smoothing out the fluctuations of flow during dryer seasons [37]. For example, the Amazon River basin, the Congo River basin, and several major rivers flowing through the world's primary tropical forests host major cities. Manaus, on the banks of the Amazon River, is a city of 2 million people; Kinshasa and Brazzaville, on the Congo River, will soon be home to 20 million people. Around the world flood plains and estuaries downstream of tropical primary forests are home to between 1.6 and 1.9 billion people [38] – a number which is growing fast [39].

Tropical primary forest catchments are also integral to coastal and marine ecosystem integrity, such as coral reefs, sea grass beds, and inshore fisheries. In the tropics, this is dubbed the 'ridge to reef' concept in landscape management, whereby the integrity of forested catchments is linked to the health of inshore marine habitats and communities [40,41]. Coral reefs, for example, are particularly vulnerable to disturbed catchments, which produce additional sedimentation and nutrient-laden river flows, both of which set in train damaging threatening pathways that degrade the important ecosystem services generated by coral reefs, such a coastal protection, fishing and collecting, and tourism [40,41].

Regional rainfall cycling

Primary tropical forests contribute to regional rainfall regimes [35,42]. This is well studied in the Amazon basin, where water transpired to the atmosphere from forest photosynthesis recirculates with moist oceanic air constantly from east to west, increasing the rainfall supporting primary tropical forests more than 3,500 km from the river's estuary on the Atlantic. Any deforestation in eastern Amazonian primary forest breaks this feedback loop – reducing rainfall and potentially leading to forest degradation inland. This regional phenomenon therefore links local actions that cause deforestation and degradation with potential continent-wide changes in rainfall and related climatic conditions, which impact both the primary forest and the livelihoods of people thousands of kilometres away.

Maintenance of forest interior micro-climate

At a local scale, the closed forest canopy of primary tropical forests create an interior microclimate that shelters the understory and maintains moist, shady, and cooler conditions, which retains more water within the ecosystem rendering it more resistant to droughts and wildfire [4]. Stable forest interior micro-climates produced in primary forests provide critical habitat

[i] See https://tfff.earth/about-tfff/

conditions for forest-dependent wildlife. These conditions are also of enormous benefit to the well-being of Indigenous forest dwellers as they generating provisioning ecosystem services, such as subsistence fruits and nuts, and other non-extractive non-forest timber products that can be sustainably harvested and sold into specialist, high-value, small-scale supply chains, which, with appropriate safeguards, will not subtract from the forest stock [43].

Taxonomic and genetic biodiversity

Primary tropical forests are the most important terrestrial ecological and evolutionary refugia for taxonomic and genetic biodiversity on the planet. They experience a climate which is conducive to year-round plant growth, resulting in high rates of plant growth and complex vegetation structure, providing a diversity of stable habitats. Primary tropical forests harbor 62% of global terrestrial vertebrate species, more than double that of any other terrestrial biome. Around 29% of global vertebrate species are endemic to tropical forests. The refugia value of primary tropical forests are based on their ecological and intrinsic values and also its importance to future generations, both within our moral community (descendants of who we can conceive) and beyond, long into the future.

There are also clear economic values associated with 'bioprospecting', which is the search for plants, animals, and microbial species for academic, pharmaceutical, biotechnological, agricultural, and other industrial purposes [44–46]. The premise of bioprospecting is that the biodiversity in a given primary forest contains genetic material and related natural compounds (a provisioning ecosystem service) of potentially huge, but unknown magnitude, which can motivate, and even finance, forest conservation [44,47]. Total monetary values for bioprospecting are, by definition, driven by the number of potential beneficiaries. Therefore, the significant costs associated with product development can be reflected in modest, but nonetheless material marginal values for tropical forest bioprospecting (e.g., the WTP per ha per year for access to a conserved forest area), particularly when the forest area is large. For example, a study by Rausser [48], recalibrated by Naidoo & Ricketts [47] estimate the WTP of pharmaceutical companies may be US$ 2.21/ha/yr, which over a large area of forest (e.g., the Kayapo people of the Amazon basin have sovereignty over 11 million ha) could generate economic value (potentially even revenue) that tip the decision-making process towards conservation projects.

Bioprospecting can have an impact on local social and economic development that can transfer wealth from the global north to the biota-rich global south, but only if benefit sharing or high value-add processes are brought into the prospecting country [45,49]. Such concerns are subject to an international protocol [ii] and an associated fund [iii]. Therefore, whilst no panacea, such approaches clearly demonstrated the economic benefits associated with the inherent value of the biodiversity hosted in primary tropical forests.

Buffer against pandemics

In December 2019 an unknown respiratory illness arose in China, which by the end of January 2020 was to become the Covid-19 global pandemic. The Asian Development Bank estimated the global economy suffered between US$ 5.8 trillion and US$ 8.8 trillion in losses (6.4% to 9.7% of global GDP) [50]. Covid-19 demonstrated the economic impact of anthropogenic pressures that facilitate the spillover of pathogens from wildlife to livestock and human populations (zoonosis) and the importance of primary forests as upstream buffers in prevention of pathogen emergence [51]. The degradation and fragmentation of primary forest has been identified as a factor in zoonosis and is becoming more frequent and intense [52]. Each year, more than five new zoonotic diseases emerge and this trend is increasingly linked to landscape-level environmental changes, such as deforestation and an increase in interactions between humans and potential vectors [53]. Whilst there are no known economic estimations of the economic value of protecting primary forests for the avoidance of global pandemics, it is the subject of significant research activity.

Preserving cultural and linguistic diversity

A nexus exists between primary tropical forest conservation, Indigenous Peoples' wellbeing, and preserving the human world's linguistic and cultural diversity [8]. Globally, Indigenous Peoples manage, or have recognised tenure rights over, approximately 38 million km^2 of land across 87 countries or politically distinct areas intersecting around 40% of all terrestrial protected areas [54]. This linguistic and cultural diversity is evident in all primary tropical rainforest. There is demonstrated spatial correlation between biodiversity loss and the world becoming less linguistically and culturally diverse [55,56].

Cultures and languages carry with them "alternative yet equally valid ways of knowing and interpreting biodiversity" [57]. The economic value of this cultural and linguistic diversity is not only manifest in the desirability of locations with rich and diverse cultural practices for eco-cultural tourism, but also in the value primary forest as a generator of value from the 'characteristics of living systems that enable education and training' (a cultural ecosystem service definition from CICES). This describes the economic value generated by the forest as a subject for scientific studies [58]. There are a few monetary valuation studies associated with tropical forests, both are from conserved forest areas, one from Malaysia and another from Ghana and though the values are modest, it nevertheless contributes towards the total ecosystem service value of primary tropical forests in language diverse areas [59,60].

CONCLUSION

To protect the world's primary tropical forests and to meet global climate, biodiversity, and human development goals, a step change in resourcing and policy support are both required [9]. Resourcing can include *private money* (investment seeking a return), *funding* (from public expenditure, not necessarily demanding a cash return on investment), *financing* (public or private debt that demands repayment and interest), *indirect resourcing* (through institutional labour), and *indirect creation of value* (for example, through the creation of new property rights, for example, creating the capacity to sell water quality units). The scale and quality of ecosystem services generated by the world's primary forest, most especially represented by the enormous asset value of its stored carbon (US$ 174 trillion and rising), is simply too considerable to not demand specific policy support and targeted resourcing. In addition, the case of the Kayapo shows that primary tropical forest protection can be achieved very cost effectively, when supported by systems of property rights and constitutional protections that recognise the sovereignty of First Nations and Indigenous Peoples. In this instance, the Kayapo have protected 11 million hectares of primary tropical forest with an annual budget of USS 2 million per year, or about US$ 4.75 per ha per year [7].

Payment for ecosystem services (PES) schemes have considerable potential to conserve biodiversity in low income and developing countries in which much of the primary tropical forest is found [61]. Yet the scale of the challenge remains contentious, as encapsulated by the question posed by Bush et al. [62]: what represents fair value for compensation for forest conservation, in this instance as a result of carbon sequestration. That is *how much is my forest carbon worth* on the supply side and *how much*

[ii] The Nagoya Protocol on Access and Benefit-sharing at https://www.cbd.int/abs/default.shtml

[iii] The Global Biodiversity Framework Fund at https://www.thegef.org/what-we-do/topics/global-biodiversity-framework-fund

should I pay for any given carbon credit on the demand side [62]. Whilst welfare estimates values, based on a full suite of ecosystem services (e.g., that represented by the SCC) describe how much a forest is *worth*, but what 'price' is *demanded* for forest conservation (e.g., carbon credits, or payments for changes in forest management) is often considerably lower. However, often such prices reflect either insufficient demand for carbon credits to meet climate objectives, or prices in equivalent local markets that do not function well anyway [62]. Conversely, welfare estimates also do not equate to a fair financial price either, as they account for non-market local factors that contribute to overall welfare, such as cultural and livelihoods risk management and if this is the price paid, it does not maximise conservation potential. The difference, and therefore the resourcing challenge, is considerable. For example, the scale of annual resource required to conserve the entire primary tropical forest in the Democratic Republic of Congo (the second largest estate) in financial terms is just under US$ 1 billion, compared to annual flow of welfare value of just over US$ 12 billion [62].

Resource mobilisation will take many forms. One emerging concept is the Tropical Forest Finance Facility (TFFF) (formerly the Tropical Forest Forever Facility), an initiative designed to motivate long-term predictable resourcing for tropical forest conservation from both public and private sources [63]. The facility will source resources from sovereign wealth funds, philanthropic foundations, and green-minded international investors to generate payments to countries based on their forest conservation (based on hectares of forest protected, in contrast to tonnes of carbon sequestered, or emissions from deforestation and degradation avoided, which is the focus of the current voluntary and compliance carbon schemes). The TFFF will also be designed to ensure that monies reach Indigenous Peoples and local communities that contribute directly to protecting forests and also to be inter-operable with existing programs, such as the Global Environment Facility (GEF), REDD+, and other carbon markets. In parallel, the Tropical Forest Mechanism (TFM) is designed along similar lines [iv], but with a less stringent restrictions on the source of resourcing and can even include resource companies [64]. Whilst such funds delink forest conservation from generating a cash flow, and instead rely on alternative investments generating the return, it nevertheless remains vital that the fund is not invested in activity that further intensify the climate and biodiversity crises and is instead invested in the equities that have positive environmental, social, and governance attributes – historically, investments that return higher yields have been those that have socialised risks as much as possible. Estimates for the scale of the challenge suggest that to support conservation in the three regions that host the majority of the world's 1.2 billion ha of tropical forests would require US$ 36 billion per year, a fraction of the value of the multi-trillion dollar carbon asset, and the equivalent of a US$ 1 levy on each barrel of oil produced per year.

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[iv] Indeed, the two schemes began as the Tropical Forests Forever Facility at COP28 in 2023 before being separated to focus on different sources of resources.

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