Quantifying Threats to Biodiversity and Prioritizing Responses: An Example from Papua New Guinea

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Abstract: Accurately identifying threats to global biodiversity is the first step towards effectively countering or ameliorating them. However, such threats are usually only qualitatively categorized, without any comparative quantitative assessment of threat levels either within or across ecosystems. As part of recent efforts in Papua New Guinea to develop a long-term strategic plan for reducing threats to biodiversity at the national level, we developed a novel and quantitative method for not only assessing relative effects of specific biodiversity threats across multiple ecosystems, but also identifying and prioritizing conservation actions best suited for countering identified threats. To do so, we used an abbreviated quantitative SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis and multivariate cluster analysis to identify the most significant threats to biodiversity in Papua New Guinea. Of 27 specific threats identified, there were nine major threats (each >5% of total) which accounted for approximately 72% of the total quantified biodiversity threat in Papua New Guinea. We then used the information to identify underlying crosscutting threat drivers and specific conservation actions that would have the greatest probability of reducing biodiversity threats across multiple ecosystem realms. We categorized recommended actions within three strategic categories; with actions within each category targeting two different spatial scales. Our integrated quantitative approach to identifying and addressing biodiversity threats is intuitive, comprehensive, repeatable and computationally simple. Analyses of this nature can be invaluable for avoiding not only wasted resources, but also ineffective measures for conserving biodiversity.

Keywords: Papua New Guinea; biodiversity; threats; conservation; SWOT analysis; ecosystem; planning; resources; prioritization

1. Introduction

The island of New Guinea (comprised of West Papua and Papua New Guinea) is the largest tropical island in the world, with a total land area of approximately 785,750 km². Due mainly to its great elevation range (sea-level to 4500 m ASL), combined with a tropical climate and diverse topography and geologic origins, Papua New Guinea (hereafter, PNG) harbors diverse and unique life zones and forested habitats not found elsewhere in the Pacific Islands [1–4] (Figures 1 and 2). After the Amazon and Congo basins, the forests
of PNG comprise the third largest expanse of tropical forest in the world and are internationally recognized for their high biodiversity and ecological importance, both locally and globally [5–7]. Indeed, some areas of PNG (i.e., the islands of the Bismarck Archipelago) are currently classified as part of a global “biodiversity hotspot” ([8,9]. Host to one of the richest assemblages of vertebrates on Earth, the forests of PNG harbor at least 1786 species of birds, mammals, reptiles, and amphibians [7]—over 5 percent of the world’s total—with many yet undiscovered and undescribed. Covering nearly 282,000 km² and 80 percent of the land mass of PNG [7], these forests have in recent decades come under increasing pressure from logging activities, agroforestry-related land clearing, mining activities, oil and gas development, and increasing subsistence agriculture arising from a rapidly increasing human population [4–11].

Figure 1. Regional map and major landmarks of PNG. From CIA World Factbook [https://www.cia.gov/library/publications/the-world-factbook/geos/pp.html (accessed on 3 June 2021)].

Figure 2. Extent and distribution of the major vegetation classes of Papua New Guinea. Data adapted from the Forest Inventory Mapping (FIM) System, sensu McAlpine and Quilley [12].
Additionally, because of PNG’s unique land tenure system and widespread dependence on subsistence farming and harvesting, PNG’s biodiversity continues to be fundamental to the health, economy, and culture of the nation’s largely rural population [8]. However, PNG’s rich and unique biodiversity is also among the most threatened, leading PNG’s government to recognize major threats to its environment from deforestation and forest degradation; illegal, unreported and unregulated fishing; pollution; industrial activities; and climate change [13–16]. Recent remote sensing images have revealed significant ongoing habitat conversion in PNG, especially of old-growth and closed-canopy forest [7]. Moreover, a broad array of ecological studies demonstrate that threats such as logging, over-hunting, pollution, and invasive species reduce the intactness of ecosystems and cause significantly reduced numbers and local extirpation of many species [17].

Recognizing PNG’s remarkable biodiversity and the threats to it, the Government of PNG and United States Agency for International Development (USAID) identified PNG as a priority country for assistance in biodiversity conservation, with funds apportioned to conduct an analysis of drivers and threats to biodiversity and a corresponding joint conservation strategy with the Government of PNG [17–20]. Consequently, the USAID requested the United States Department of the Interior’s International Technical Assistance Program (DOI-ITAP) to provide technical support for a national biodiversity threat assessment of PNG.

The assessment was designed to provide a well-documented, objective analysis that (1) identifies and quantifies specific threats to PNG’s biodiversity in marine, inland water, and terrestrial ecosystem realms, and (2) identifies the actions necessary to most effectively address these threats and benefit biodiversity conservation broadly in the country [21]. As such, the assessment builds upon, amplifies and increases precision of previous efforts at biodiversity threat identifications and assessments e.g., [22–29]. For this study, we define “terrestrial ecosystem” as all land-based environments and habitats, “inland water ecosystem” as all freshwater lentic and lotic systems, including all deltaic and brackish coastal and estuarine (mesohaline) zones, while “marine ecosystem” includes all euhaline offshore territorial waters and coral reefs. Threats to biodiversity are defined as those human activities that reduce the viability of an ecosystem, species or other types of biodiversity. This study uses threat nomenclature consistent with the IUCN lexicon developed by Salafsky et al., [30] but customized to PNG. The overarching goal was to provide a strong rationale for future biodiversity projects that USAID and its partners in PNG could develop as part of a long-term investment in PNG’s unique and globally important biodiversity.

2. Materials and Methods

2.1. Threats Assessment

2.1.1. Literature Review

The DOI-ITAP assessment team (n = eight persons) first conducted an exhaustive and comprehensive review of the available literature—published and non-published—relative to biodiversity, resource conservation and associated issues in PNG. During this review, over 300 documents were obtained and reviewed, a complete bibliography of which is found in Brown et al. [21]. All documents so obtained were made available to all team members via internet using a shared Google Drive® storage and inventory system.

2.1.2. In-Country Site Visits and Interviews

In addition to literature-sourced information, the team also conducted numerous in-country interviews with PNG government and non-government entities. These interviews were conducted during two separate visits by team members to PNG; the first in November 2016, and the second during February–March 2017. During these visits, the team met with more than 110 individuals representing more than 30 organizational stakeholders having direct involvement or interests in PNG biodiversity see [21]. The assessment team also conducted site visits to several representative ecoregions of PNG to obtain additional first-hand information on current biodiversity threats and status thereof.
2.1.3. Quantitative Threat Assessment and Ranking

To provide an objective, quantitative and data-driven method for assessing relative threat levels, we used a modified version of quantitative SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis [31]. Quantitative SWOT analysis has several desirable characteristics as applied to environmental assessments. The method is simple, versatile, repeatable and intuitive. Importantly, the ability to effectively combine mixed data (cardinal, categorical, and continuous) together with multidisciplinary expert knowledge [27,31] into a single structured model provides a comprehensive, practical and uniform metric for comparing multiple threats and prioritizing biodiversity conservation strategies [29,31]. Because our specific objective was to assess current threats to biodiversity, we therefore abbreviated the SWOT approach to focus only on the category of “Threats”.

Specific threats were identified based on the literature review, and the collective knowledge and experience of team members, several of which (G.D., D.K., D.P.) also had extensive prior experience working in PNG. These threat tables were also periodically updated and refined during the analytical process as additional information became available. Once a complete listing of threats was compiled, a quantitative SWOT template [31] was used to assign a “weight” ranging from 100–1000 for each threat in terms of its relative impact (i.e., 100 = very minor impact; 1000 = extreme impact) on biodiversity in other similar settings. That is, we considered how each threat was known to affect biodiversity in other tropical, insular environments (e.g., Madagascar, Hawaii, Hispaniola, Indonesia, Mauritius, Jamaica). Threat weightings were based on the expert-based team consensus, the members of which all had prior or ongoing experience working in tropical, insular environments. The value of expert-based assessments in ecology and conservation has become increasingly recognized, particularly in cases of varying degrees of epistemic uncertainty, as in this assessment e.g., [27,29,31]. Once all threat weightings were determined, an importance coefficient (IC) was computed for each threat that reflected its relevance to overall threat levels. The individual ICs were calculated as follows: 

\[ IC_i = \frac{W_i}{\sum W_{i-n}} \]

where \( W_i \) is the respective threat weight, \( \sum W_{i-n} \) is the sum of all individual threat weights, and thus \( \sum IC_{i,n} = 1 \). Because there were ecosystem-specific differences in both the number and impact of individual threats, the individual threat weights and ICs also varied accordingly among the three ecosystem categories.

Threat levels were also affected by three additional coefficients: spatial, temporal and probability of occurrence. The spatial coefficient (SC) reflects the geographic extent of a given threat across PNG. If the threat applied equally over the entire country, the SC was 1. However, if the threat was spatially disproportional, then the SC was allocated accordingly. Spatial coefficients for each threat were determined based on a combination of published reports, PNG government documents and reports, and geospatial evaluation using overlaid data themes. Similarly, the temporal coefficient (TC) applies to threats that affect the country only periodically or cyclically during any given year (e.g., anthropogenic fires). Finally, the probability of occurrence (POC) coefficient indicates the likelihood that a given threat will be present or occur in any given year. A POC of 1 indicates that the factor is always present or occurs each year. Thus, these coefficients attenuate the relative weight (i.e., IC) of individual threats according to PNG-specific conditions. For example, two different threats may have the same general impact (i.e., weight) on biodiversity, but if one only affects 10 percent of the country, while the other affects 95 percent, then the relative impact (i.e., ICA) of the latter would be higher. All coefficients were based on existing data and information extracted from the available published literature and PNG Government reports and policy documents. Any threats not subject to measurable spatial, temporal or probability of occurrence variations were assigned default coefficients of 1, respectively.

Finally, for each threat the team assigned on a scale of 0–10, two numerical values for each threat level: optimal and actual. For any given threat, optimal level was assigned a default value of 10, as it represents the ideal scenario in terms of biodiversity conservation. Most critical however, were the values for actual level, as they represented the team consensus on the actual state of the threats for PNG. Actual values were based on how,
or to what extent, the threats currently exist or operate in PNG relative to their impact on biodiversity. In this case, a value of 10 represents either absence of the threat, or the complete mitigation or abatement of it. Conversely, a value of zero would represent an imminent, existential threat to those aspects of biodiversity thus affected (i.e., “worst case scenario”). Importantly, estimates of actual values also considered relative impacts on overall biodiversity by the specific threats. For example, two different threats could each have the same weight and coefficients, but if one affects areas of greater species diversity and/or endemism (e.g., montane rainforests), then the actual value for this threat would be scored lower (i.e., greater severity) than that of a threat affecting primarily areas of lesser biodiversity (e.g., coastal scrub forests). The team used all available information—published, non-published and geospatial—as well as information obtained from in-country interviews and discussions, in order to assign actual values. For this estimate, the initial nonbiased starting point was a value of five. The team then decided whether the impact of a given threat on biodiversity in PNG was less severe (>5) or more severe (<5), and to what degree.

To estimate and quantitatively compare individual threats using the SWOT template, three indices were also calculated: optimal quality (OQ), actual quality (AQ), and the quality deviation index (QD). The OQ is the highest potential “quality” for the threat, while the AQ is the observed or actual quality based on the PNG-specific team assessments. For each threat, these indices were obtained by multiplying the associated optimal and actual quality values by all four corresponding coefficients. The final quality indices (optimal, actual) were then computed as the sum of the previous values as follows:

\[ Q_{o,a} = \sum_{i=n} (V_{o,a} \times I_i \times S_i \times T_i \times P_i); \]

where:

- \( Q_{o,a} \) = Threat level (optimal, actual).
- \( V_{o,a} \) = Optimal and actual values, respectively, of each threat.
- \( I_i \) = Importance coefficient of each threat.
- \( S_i \) = Spatial coefficient of each threat.
- \( T_i \) = Temporal coefficient of each threat.
- \( P_i \) = Probability of occurrence coefficient of each threat.

And, where the quality deviation index (QD) = \( Q_o - Q_a \).

The QD provides detailed and valuable insights for threat evaluation. Analysis of individual partial QDs can reveal whether certain threats to biodiversity could feasibly be mitigated or improved by conservation actions. For example, some threats may be impractical or impossible to improve over the time frame of interest. Other factors however, may be more amenable to control or reduction via conservation actions. Thus, the relative contributions of individual threats to the total QD can be used to identify where specific conservation efforts (i.e., resource allocations) may have the greatest positive impact on biodiversity conservation. For instance, if threats “x” and “y” contribute 23 percent to the overall threat QD, then effective mitigation or reduction of those threats may reduce biodiversity threat level by a similar amount commensurate with conservation success see [31]. Examination of the component (i.e., ecosystem) subtotals for threat percentages can also indicate which ecosystem(s) face greater overall threat levels.

Finally, once overall percentages were calculated for all threats, we then assigned each threat to one of three practical and intuitive categories: High, Medium, and Low. We defined “High” threats as those factors currently contributing to substantial (>5% of total threat) ongoing biodiversity loss, “Medium” threats as those which have the potential to become more serious (i.e., High) threats to biodiversity in the immediately foreseeable future, and “Low” threats as those factors which are not considered to become significant causes of biodiversity loss in PNG in the immediately foreseeable future. For this, we defined “immediately foreseeable future” as a 5-year time horizon from date of the assessment.

Because the categorization of threats was based on their quantitative contributions to the overall biodiversity threat in PNG, we used multivariate cluster analysis as a quantitative threat classification method [32]. Specifically, we used a 3-centroid Euclidian distance
model to assign individual threat percentages to one of three threat categories [33]. This allowed us to base our threat classifications on the actual data structure, rather than on any arbitrary or subjective considerations [21]. Threat classifications are presented graphically as a dendrogram generated from the cluster analysis. All statistical calculations were performed using the MINITAB® Version 13 Statistical Package for Windows®.

2.2. Situation Modeling

We used Situation Model (SM) guidance provided by USAID [34] to evaluate the biodiversity threat context, utilizing our literature review, in-country observations and discussions, as well as our SWOT and geospatial analyses [21]. Situation Modeling has been used for over two decades in the fields of public health and international development, and also provides a concise and effective way of depicting relationships among factors which affect biodiversity [34]. We relied partially upon the generic tropical forest and Philippines-oriented terrestrial ecosystem SM, as well as guidelines for the level of detail about drivers and threats to include [34,35]. Detailed descriptions and methods for constructing SMs are found in USAID [34].

Drivers, threats, and stressors identified were consistent with those identified in the USAID Tropical Forestry and Biodiversity Conservation Assessment (i.e., climate change, overexploitation and unsustainable harvest, habitat loss, invasive species and pollution) [36]. Our process enabled us to develop a comprehensive SM for biodiversity including terrestrial, inland water, and marine systems, as well as social, economic and governance drivers.

Within each strategic approach, we created recommendations at two different scales: community and national. Community level, for the purposes of this assessment, is defined to include Provincial, District and local-level governments along with local clan and village governance. The community-level recommendations focus on engaging communities in biodiversity conservation through education, training, and land use planning. The national-level recommendations focus on supporting government and educational institutions and other civil society. Government agencies can provide policies and regulation to guide conservation, law enforcement, and science-based technical assistance to communities and NGOs working in conservation. Higher education institutions can provide training and education across a wide-range of topics to support both the central government and local communities to develop a cohort of PNG citizens who are trained and empowered in conservation science and practice.

2.3. Results Chains and Response Prioritizations

To develop specific recommendations for biodiversity threat reduction we also looked at each of the “High” threats identified in the SWOT analysis and then identified those strategic approaches that could alter the linkages between drivers and threats or reduce the effect of the threats to biodiversity [36,37]. We then evaluated all potential strategic approaches relative to how many of the “High” threats each approach addressed. We distilled this into three primary strategic approaches: (1) Strengthening capacity for environmental decision-making, (2) Legal and policy education and training, and (3) Integrated land use planning. Although priority was given to addressing the top threats, the recommended strategic approaches also simultaneously address a large number of lesser (Medium, Low) threats. We used Results Chains to clearly illustrate the interactive linkages between recommended actions and desired results across all three strategic approaches at both the community and national levels [21,37]. Detailed descriptions and methods for constructing Results Chains are found in USAID [37].

3. Results

3.1. SWOT Threat Assessment and Rankings

Of the 27 individual threats identified across all ecosystem realms, nine (9) were ranked as “High”, six (6) were ranked as “Medium”, and twelve (12) were ranked as “Low”
threats to biodiversity in PNG during the immediately foreseeable future (Figure 3 and Table 1). The complete composite SWOT analysis template is presented in Appendix B. These threat assessments took into consideration relative differences in overall impacts of specific threats on PNG biodiversity. For example, “undocumented harvests” of timber was classified as currently a “Low” threat. This is because most such harvests in PNG are conducted in areas previously degraded by selective logging (as opposed to primary forests), and by small independent operators (e.g., “walkabout sawmills). Accordingly, the overall biodiversity impact of such harvests was considered a lesser threat (over next five years) than that of other broader threats such as the clear cutting or the selective commercial logging of more intact primary forests. Similarly, our analyses categorized “rates of harvest” of timber as a “Medium” threat over the next five years. This was because this threat, by definition, affects areas previously degraded by selective logging (Appendix A). Thus, the overall impact on biodiversity is primarily—but not limited to—that of delaying or interrupting secondary succession and the attendant recovery or restoration of biodiversity elements previously lost to other factors. Nevertheless, because this threat occupied the top position in the “Medium” category (Table 1), it has the potential to become a more serious threat over perhaps a longer time horizon than that considered by this study.

By ecosystem category, the SWOT results indicated that the greatest proportion (approximately 40%) of the total threat to PNG biodiversity directly affects the terrestrial ecosystem (Appendix B), with the inland water and marine ecosystems subjected to 33 percent and 27 percent of the overall threat, respectively. Moreover, of the nine threats ranked as “High”, seven were threats common to two or more ecosystems, while two (i.e., IUU marine fishing, regulated commercial marine fishing) were specific to the marine ecosystem. In aggregate, the nine major threats accounted for approximately 72% (average 8% each) of the total quantified biodiversity threat in PNG (Appendix B). Clearly, in terms of overall biodiversity impact, these highest ranked threats are quantitatively noteworthy as reflected by their distinct “lineage” identified via the cluster analysis (Figure 3), compared to “Medium” and “Low” ranked threats which accounted for a remaining 16 percent (average 2.7%) and 12 percent (average 1%), respectively. In terms of overall impact on PNG biodiversity, “High” threats were on average three times more severe than “Medium” threats, which were in turn about three times more severe on average than “Low” ranked threats. Importantly for resource allocation purposes, the seven “High” threats that are shared by multiple ecosystems also accounted for 57 percent of the total biodiversity threat, and were also primarily terrestrial in origin (with IUU fishing and commercial marine fishing being the exceptions). Indeed, of the 27 total identified biodiversity threats, closer examination of only those shared by all three ecosystem realms reveals that these cross-realm threats (n = 8), and which originate within the terrestrial component also account—either directly or indirectly—for approximately 45 percent of the overall threat to biodiversity across all ecosystems in PNG (Appendix B). This suggests that conservation efforts focused on countering or mitigating the broader suite of these and other cross-realm terrestrial based threats would have the greatest positive impact in reducing current overall biodiversity loss in PNG, via a “multiplier effect” across multiple ecosystems.

**Figure 3.** Dendrogram depicting the ranking and categorization of 27 specific threats to biodiversity in Papua New Guinea based on quantitative SWOT and multivariate cluster analyses. Red (1–9) denotes “High” threats, Green (10–15) denotes “Medium” threats, and Blue (16–27) denotes “Low” threats.
Table 1. Hierarchical listing of specific biodiversity threats in Papua New Guinea based on quantitative SWOT and multivariate cluster analyses. Heading colors and numbers (e.g., HIGH 1–9) correspond to those of the cluster analysis dendrogram (Figure 3). Threat nomenclatures and associated definitions are in Appendix A.

| Threat Category                          | HIGH (1–9)                  | MEDIUM (10–15)            | LOW (16–27)               |
|-----------------------------------------|-----------------------------|---------------------------|---------------------------|
| Clear-cutting (all forms)               | Rates of harvest            | Subsistence agriculture   | Anthropogenic fires        |
| Commercial agroforestry                 | Oil and gas extraction      | Subsistence hunting       | Development/village expansion |
| IUU marine fishing                      | Fuel wood harvesting        | Infrastructure developments| Dams/hydroelectric projects |
| Selective cutting                      |                            |                           |                          |
| Invasive species                       |                            |                           | Unregulated plant/wildlife trade |
| Pollution                               |                            |                           | Regulated marine fishing (artisanal) |
| Regulated commercial marine fishing     |                            |                           | Traditional forest orchards |
| Harvest volumes                        |                            |                           | Aquaculture                |
| Mineral extraction                     |                            |                           | Renewable energy projects  |
|                                        |                            |                           | Hunting for cultural items |
|                                        |                            |                           | Seabed mining              |
|                                        |                            |                           | Undocumented harvests      |
|                                        |                            |                           | Regulated plant/wildlife trade |

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3.2. Situation Model

We identified 10 drivers, 16 threats, and 7 stressors that impinge on biodiversity in PNG (Figure 4). Driver and threat categories are mostly synoptic and/or multi-faceted and apply broadly across PNG, as opposed to being highly-specific, unidimensional, or only applicable to tightly-constrained geographic areas or ecosystems. To simplify the visual presentation in the situation model (SM), we grouped some threats that were analyzed separately in the SWOT analysis. For example, the “timber harvest” threat was broken out into five subcategories that were each scored separately for SWOT analysis (see Table 1, Appendix B). Our SM follows the guidance from USAID in which drivers represent ultimate factors, usually social, economic, political, institutional or cultural, that enable or amplify the occurrence of one or more threats, which are the proximate human activities.
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Figure 4. Situation Model based on quantitative assessment of biodiversity threats and associated drivers in Papua New Guinea. Bidirectional vectors represent interactions between component factors.

3.3. Results Chains and Response Prioritizations
Our recommendations resulted from extensive in-country discussions with stakehold-
ers, a broad literature review, results of the quantitative SWOT analysis, and consensus of
the assessment team. For each Strategic Approach we developed Results Chains [37] to link
our recommendations to the Situation Model and SWOT analysis (Figures 5–7). The Results
Chain linkages also provide a useful graphic-based guide for prioritizing recommended
actions at both the national and local community levels. For example, those actions that
influence or promote the greatest number of results could be considered as greater priority
relative to those of lesser functional linkages.
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Figure 5. Results Chain for strategic goal of Strengthening Capacity for Environmental Decision-making in Papua New Guinea.

Figure 6. Results Chain for strategic goal of Legal and Policy Education and Training in Papua New Guinea.

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Figure 6. Results Chain for strategic goal of Legal and Policy Education and Training in Papua New Guinea.
4. Discussion

The primary threats to biodiversity (those in the “High” category) identified in the assessment and combined for PNG’s terrestrial, inland water, and marine ecosystems were: clear-cutting of forests; commercial agroforestry; illegal, unreported, and unregulated marine fishing; selective cutting (timber harvest); invasive species; pollution; regulated commercial fishing; timber harvest volumes; and mineral extraction. Through situation modeling, the underlying drivers were linked to these threats; these drivers are numerous and interconnected. Population growth, human migration, and climate change are ultimate drivers from which flow other, more proximate drivers, and resulting threats to biodiversity. The chief proximate drivers (those we identified as the best opportunities for intervention to address threats to biodiversity) included regulatory efforts, capacity enhancement, land tenure and protected area systems, internal and external demand for resources, and the evolving cash economy. Through the consultative process and results-chains exercises, and in light of these key drivers, we developed a set of three strategic approaches, each containing recommended programmatic actions at community and national levels to guide investments to help conserve PNG’s biodiversity. Thus, our assessment and recommendations are consistent with the concept of “cross-realm decision-making”, as recommended by Tulloch et al. [38].

A common thread throughout our in-country stakeholder interviews was the need to enhance the capacity of PNG citizens and institutions regarding environmental and biodiversity topics and best practices. The need for capacity enhancement stretches from individuals in rural communities to employees of government agencies in the capital of Port Moresby. Developing a cadre of people, across PNG, familiar with and educated in environmental and biodiversity topics, as well as other supporting disciplines such as finance and project management, will help to reduce threats to biodiversity across the landscape, provide sustainable opportunities for PNG communities, and create long-term conditions for successful conservation in PNG.
lands to prevent inequitable and abusive land acquisitions and unsustainable resource exploitation by outside interests. For example, there have been numerous cases of rural communities and clans effectively losing permanent control over their legally-owned lands to unscrupulous developers and foreign resource extraction companies, e.g., [40–43]. Assisting local communities with the often complex legal and ecological issues associated with protecting and sustainably managing their lands can yield substantial dividends in terms of biodiversity conservation, including in development of protected areas. Probably nowhere in the world presents a better setting for an effective “bottom up” approach to natural resource management and conservation, e.g., [43]. Interestingly, because of both the weak central government and the community-based land tenure system of PNG, traditional environmental “law enforcement” (i.e., “reactive model”) is largely supplanted by local community vigilance and control. This is why increasing capacity for effective environmental decision-making and environmental protection (i.e., “proactive model”) at the local, community level is likely a more effective approach to long-term biodiversity conservation and associated enforcement issues in PNG. Nevertheless, in those inevitable cases in which the legal system must ultimately intervene, having a judiciary that is fully cognizant and understanding of the ecological, social and economic impacts of illegal appropriations and attendant natural resource abuse may more likely result in equitable judgments that protect and perpetuate not only citizen rights, but also the biodiversity of PNG. Indeed, we consistently heard from in-country stakeholders and regulators about the overwhelming need to provide education and training to legislators, regulators and policy implementers at all levels of government, from communities up to the national level, concerning existing laws, their specific mandates related to natural resource conservation, how to consistently coordinate across government, and how to implement and enforce existing laws and policies. Additionally, by providing education and training concerning existing laws, the respective governmental levels may learn what regulatory tools may be deficient or absent, and subsequently develop or amend them.

Land use planning, at both the community and national levels, was identified as a strategic approach that could help reduce threats from logging, agroforestry, mineral extraction, and overfishing as well as provide options for long-term sustainable management of PNG lands. For this study, land use planning includes all terrestrial and aquatic resources, including freshwater and marine, and includes components that contribute to sustainable livelihoods, economic opportunities, or other direct benefits to the community, in a relatively short timeframe. Land use planning can help communities identify lands or waters suitable for agriculture, fishing or hunting, village sites, and protected areas. At a national level, coordinated use of biological and geospatial data can identify suitable lands for biodiversity conservation and lands better suited for resource extraction. Land use planning helps prepare for population growth and climate change adaptation, top drivers of biodiversity loss in PNG, by identifying zones of differential land use and areas to be set aside for biodiversity conservation.

5. Conclusions

Attempts to address threats to biodiversity through traditional conservation and development paradigms that have worked in other parts of the world likely will fail in PNG without adapting activities and expectations to unique local cultures and contexts see, e.g., [44–47]. PNG is singular in the world with regard to its communal land tenure structure and clan-based culture, which effectively divides the island into over 840 societies [21]. To be successful, conservation interventions in PNG must be deliberative, iterative, carefully considered, led by PNG nationals, supported over many years or decades, and yield both immediate and long-term benefits to affected communities. In addition, operational costs in PNG are extraordinarily high, thus conservation intervention costs are likewise much higher than in other parts of the world, and in-country conservation efforts therefore must be well and consistently funded. Biodiversity conservation in PNG is exceedingly challenging, slow, and costly, but the alternative—the irrevocable loss of the unique biolog-
ical and cultural richness of this island nation—is unimaginable. The combined actions recommended in this study could deliver a strategic, cost-effective, and lasting legacy for PNG’s biodiversity and people.

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

**Appendix A**

Working definitions of the 27 distinct threats to biodiversity in Papua New Guinea identified for quantitative SWOT analysis.

1. **CLEAR-CUTTING:** The complete removal and elimination of forests and forested land cover, regardless of forest type/location.
2. **SELECTIVE-CUTTING:** The harvest and removal of trees from forests based on such criteria as size, form, or species and which leaves other non-target trees in place.
3. **HARVEST VOLUMES:** Total amount of timber removed from a given forested area(s) during timber harvests, usually measured in terms of stand basal area or cubic meters of merchantable wood.
4. **RATES OF HARVEST:** The time period (rotation) between successive loggings of a given forested tract or area.
5. **UNDOCUMENTED HARVESTS:** Removal of timber from a forest without official government and/or landowner sanction, nor with any archival records of such. Includes non-commercial small-scale reentry logging of previously logged areas.
6. **COMMERCIAL AGROFORESTRY:** Large-scale conversion of forests to production of agricultural products, typically for export (e.g., oil palm, tea, coconuts). This includes land clearing associated with SABLs (Special Agricultural and Business Leases).
7. **SUBSISTENCE AGRICULTURE:** Small-scale agricultural activities primarily for local consumption by individual families or villages. Includes small-scale production of agricultural products for sale in local markets or villages.
8. **MINERAL EXTRACTION:** All forms of mining (e.g., gold, copper, chromium, nickel) and associated activities. Does not include “seabed mining” which is considered a distinct and separate threat in this assessment.
9. OIL AND GAS EXTRACTION: All activities associated with the exploration, acquisition, and distribution of naturally occurring raw petroleum products (i.e., crude oil, natural gas).

10. DEVELOPMENT/VILLAGE EXPANSION: The increase in geographic extent (“footprint”) of a given village. This includes the establishment of new villages due to population increases in existing villages.

11. ANTHROPOGENIC FIRES: Fires started in, or spread to, forested or other areas by human activities, such as from land-clearing activities, hunting activities, cooking fires, burning of garbage, or arson.

12. INFRASTRUCTURE DEVELOPMENTS: Increases in the physical structure(s) associated with human settlements and activities. Includes roads, bridges, communication towers, shopping centers, etc.

13. INVASIVE SPECIES: Any non-native organism (including plants, insects, vertebrates, fungi, diseases) that become – or may become – established in a given area, and which may eliminate, replace, infect, parasitize, or otherwise out-compete native species.

14. SUBSISTENCE HUNTING/FISHING/HARVESTING: The harvesting of wild animals (e.g., birds, mammals, reptiles, fish, mollusks) for non-commercial personal consumption by individuals, families, or villages.

15. HUNTING FOR CULTURAL ITEMS: The harvesting of wild animals (e.g., birds, mammals, reptiles, mollusks) to obtain parts of said animals for use in traditional or ceremonial objects or rituals.

16. PLANT AND WILDLIFE TRADE (REGULATED): The commercial exploitation of native plants and animals according to established laws and regulations.

17. PLANT AND WILDLIFE TRADE (UNREGULATED): The commercial exploitation of native plants and animals without established laws and regulations or other such guidelines or controls. Includes all forms of “illegal” trade and trafficking.

18. TRADITIONAL FOREST ORCHARDS: The long-standing Melanesian practice of the small-scale selective planting and inter-cropping of various tree species in a given area in order to provide a varied and long-term source of fruits, nuts, wood, fiber and other useful products for personal use and consumption.

19. FUEL WOOD HARVESTING: Cutting and/or collection of wood from the forest for use in household cooking or heating.

20. DAMS/HYDROELECTRIC PROJECTS: The use of artificial structures for impeding or altering stream flows for production of electricity, flood control, or to provide sources of irrigation water.

21. RENEWABLE ENERGY PROJECTS: Production of electricity via solar or wind power.

22. POLLUTION: Any environmental contaminants resulting from human activities. Includes household sewage, solid waste, industrial effluents, and agricultural chemicals.

23. REGULATED MARINE FISHING (ARTISANAL): Small-scale harvesting of fish or other aquatic organisms, for commercial or non-commercial purposes, via use of traditional gear and techniques and according to established laws and regulations.

24. AQUACULTURE: The production – commercial or otherwise – of aquatic organisms in controlled structures or environments. Includes activities such as “fish farming”.

25. IUU MARINE FISHING: The “Illegal, Unregulated, Unreported” harvesting of fish or other marine species for commercial purposes. In PNG, includes (but not limited to) harvesting of tuna stocks and bêche de mer (sea cucumber) by foreign fishing fleets.

26. REGULATED MARINE FISHING (COMMERCIAL): The large-scale commercial harvest of marine fisheries resources according to established laws and regulations.

27. SEABED MINING: The extraction of submerged minerals and resources from the sea floor, either by dredging sand and/or sediments, or lifting benthic material in any other manner.

Appendix B
Table A1. Papua New Guinea biodiversity threat analysis complete template based on quantitative SWOT methods. Note that TOTAL % represents the total contribution of individual threats to overall biodiversity threat across all three ecosystem realms. ICA represents the product of (IC * SC * TC * POC).

| No | THREATS | TERRESTRIAL | Weight | IC  | SC  | TC  | POC | ICA  | Optimal | Actual | OptimalQ | Actual Q | QD  | %TQD | TOTAL% |
|----|---------|-------------|--------|-----|-----|-----|-----|------|---------|--------|----------|----------|-----|------|--------|
| 1.1 | Timber harvest | | | | | | | | | | | | | |
| 1.1.1. Clear cutting | | 1000 | 0.042 | 0.39 | 1 | 1 | 0.016 | 10 | 6 | 0.1625 | 0.0975 | 0.065 | 3.89 | 12.71 |
| 1.1.2. Selective cutting | | 600 | 0.025 | 0.39 | 1 | 1 | 0.01 | 10 | 4 | 0.0975 | 0.039 | 0.059 | 3.5 | 8.66 |
| 1.1.3. Harvest volumes | | 400 | 0.017 | 0.39 | 1 | 1 | 0.007 | 10 | 5 | 0.065 | 0.0325 | 0.033 | 1.94 | 5.52 |
| 1.1.4. Rates of harvest (rotations) | | 600 | 0.025 | 0.39 | 1 | 1 | 0.01 | 10 | 4 | 0.0975 | 0.039 | 0.059 | 3.5 | 3.5 |
| 1.1.5. Undocumented harvests | | 100 | 0.004 | 0.39 | 1 | 1 | 0.002 | 10 | 5 | 0.0163 | 0.0081 | 0.008 | 0.49 | 0.49 |
| 1.2 | Commercial agroforestry (including SABLs) | | | | | | | | | | | | | |
| 1.3 | Subsistence agriculture | | | | | | | | | | | | | |
| 1.4 | Mineral extraction | | | | | | | | | | | | | |
| 1.5 | Oil and gas extraction | | | | | | | | | | | | | |
| 1.6 | Development/village expansion | | | | | | | | | | | | | |
| 1.7 | Anthropogenic fires | | | | | | | | | | | | | |
| 1.8 | Infrastructure developments (roads, bridges, urbanization) | | | | | | | | | | | | | |
| 1.9 | Invasive species | | | | | | | | | | | | | |
| 1.10.1. Subsistence hunting | | | | | | | | | | | | | |
| 1.10.2. Hunting for cultural items | | | | | | | | | | | | | |
| 1.10.3. Plant and wildlife trade (regulated) | | | | | | | | | | | | | |
| 1.10.4. Plant and wildlife trade (unregulated) | | | | | | | | | | | | | |
| 1.10.5. Traditional (subsistence) forest orchards | | | | | | | | | | | | | |
| 1.10.6. Fuel wood harvesting | | | | | | | | | | | | | |
| 1.11 | Dams/hydroelectric projects | | | | | | | | | | | | | |
| 1.12 | Renewable energy projects (wind, solar) | | | | | | | | | | | | | |
| 1.13 | Pollution (residential and industrial effluents, solid waste, agricultural chemicals) | | | | | | | | | | | | | |
| **Subtotals** | | 11,400 | 0.475 | | | | | | | | | | | | 40.36 |

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Table A1. Cont.

| No | THREATS                      | Weight | IC   | SC  | TC  | POC | ICA | Optimal | Actual | Optimal Q | Actual Q | QD   | %TQD | TOTAL% |
|----|------------------------------|--------|------|-----|-----|-----|-----|---------|--------|-----------|----------|------|------|-------|
| 2.1 | Timber harvest               |        |      |     |     |     |     |         |        |           |          |      |      |       |
|     | 2.1.1. Clear cutting         | 1000   | 0.042| 0.39| 1   | 1   | 0.016| 10      | 4      | 0.1625    | 0.065    | 0.098 | 5.83 |
|     | 2.1.2. Selective cutting     | 600    | 0.025| 0.39| 1   | 1   | 0.01  | 10      | 5      | 0.0975    | 0.0488   | 0.049 | 2.92 |
|     | 2.1.3. Harvest volumes       | 400    | 0.017| 0.39| 1   | 1   | 0.007| 10      | 4      | 0.065     | 0.026    | 0.039 | 2.33 |
| 2.2 | Commercial agroforestry (including SABLs) | 1000   | 0.042| 0.32| 1   | 1   | 0.013| 10      | 4      | 0.1333    | 0.0533   | 0.08  | 4.79 |
| 2.3 | Subsistence agriculture     | 500    | 0.021| 0.2  | 1   | 1   | 0.004| 10      | 6      | 0.0417    | 0.025    | 0.017 | 1    |
| 2.4 | Consumptive use of natural resources |        |      |     |     |     |     |         |        |           |          |      |      |       |
|     | 2.4.1. Subsistence fishing/harvesting | 250    | 0.01 | 0.33| 1   | 1   | 0.003| 10      | 8      | 0.0344    | 0.0275   | 0.007 | 0.41 |
|     | 2.4.2. Regulated marine fishing (artisanal) | 300    | 0.013| 0.1  | 1   | 1   | 0.001| 10      | 8      | 0.0125    | 0.01     | 0.003 | 0.15 |
|     | 2.4.3. Plant/wildlife trade (regulated) | 200    | 0.008| 0.1  | 1   | 1   | 0.001| 10      | 7      | 0.0083    | 0.0058   | 0.003 | 0.15 |
|     | 2.4.4. Plant/wildlife trade (unregulated) | 300    | 0.013| 0.1  | 1   | 1   | 0.001| 10      | 7      | 0.0125    | 0.0088   | 0.004 | 0.22 |
| 2.5 | Aquaculture                 | 300    | 0.013| 0.33| 1   | 1   | 0.004| 10      | 6      | 0.0413    | 0.0248   | 0.017 | 0.99 |
| 2.6 | Renewable energy projects (wind, solar) | 200    | 0.008| 0.59| 1   | 1   | 0.005| 10      | 9      | 0.0492    | 0.0443   | 0.005 | 0.29 |
| 2.7 | Pollution (residential and industrial effluents, solid waste, agricultural chemicals) | 600    | 0.025| 0.76| 1   | 1   | 0.019| 10      | 7      | 0.19      | 0.133    | 0.057 | 3.41 |
| 2.8 | Oil and gas extraction      | 500    | 0.021| 0.25| 1   | 1   | 0.005| 10      | 8      | 0.0521    | 0.0417   | 0.01  | 0.62 |
| 2.9 | Mineral extraction          | 400    | 0.017| 0.66| 1   | 1   | 0.011| 10      | 6      | 0.11      | 0.066    | 0.044 | 2.63 |
| 2.1 | Dams/hydroelectric projects | 1000   | 0.042| 0.13| 1   | 1   | 0.005| 10      | 7      | 0.0542    | 0.0379   | 0.016 | 0.97 |
| 2.11 | Invasive species            | 700    | 0.029| 0.8  | 1   | 1   | 0.023| 10      | 6      | 0.2333    | 0.14     | 0.093 | 5.58 |
| 2.12 | Infrastructure developments (roads, bridges, urbanization) | 400    | 0.017| 0.3  | 1   | 1   | 0.005| 10      | 8      | 0.05      | 0.04     | 0.01  | 0.6  |
|     | Subtotals                   | 8650   | 0.36 |     |     |     |     |         |        |           |          |      |      | 32.9 |
Table A1. Cont.

| No | THREATS TERRESTRIAL                                                                 | Weight | IC  | SC  | TC  | POC | ICA  | Optimal | Actual | Optimal | Actual | Q     | QD    | %TQD | TOTAL% |
|----|-------------------------------------------------------------------------------------|--------|-----|-----|-----|-----|------|---------|--------|---------|--------|-------|-------|-------|--------|
| 3.1 | Timber harvest (considered due to sediment transport, etc.)                         |        |     |     |     |     |      |         |        |         |        |       |       |       |        |
|     | 3.1.1. Clear cutting                                                                 | 300    | 0.013| 1   | 1   | 1   | 0.013| 10      | 6      | 0.125   | 0.075  | 0.05  | 2.99  |       |        |
|     | 3.1.2. Selective cutting                                                             | 150    | 0.006| 1   | 1   | 1   | 0.006| 10      | 4      | 0.0625  | 0.025  | 0.0375| 2.24  |       |        |
|     | 3.1.3. Harvest volumes                                                               | 100    | 0.004| 1   | 1   | 1   | 0.004| 10      | 5      | 0.0417  | 0.0208 | 0.0208| 1.25  |       |        |
| 3.2 | Consumptive use of natural resources                                                |        |     |     |     |     |      |         |        |         |        |       |       |       |        |
| 3.2.1. | Subsistence fishing/harvesting                                                      | 200    | 0.008| 0.01| 1   | 1   | 0    | 10      | 6      | 0.0008  | 0.0005 | 0.0003| 0.02  | 8.72  | 5.98  |
| 3.2.2. | IUU marine fishing                                                                   | 700    | 0.029| 1   | 1   | 1   | 0.029| 10      | 5      | 0.2917  | 0.1458 | 0.1458| 8.72  | 8.72  | 8.72  |
| 3.2.3. | Regulated marine fishing (commercial)                                               | 600    | 0.025| 1   | 1   | 1   | 0.025| 10      | 5      | 0.25    | 0.15   | 0.1   | 5.98  | 5.98  | 5.98  |
| 3.2.4. | Regulated marine fishing (artisanal)                                                | 200    | 0.008| 1   | 1   | 1   | 0.008| 10      | 8      | 0.0833  | 0.0667 | 0.0167| 1     |       |       |
| 3.3  | Aquaculture                                                                          | 100    | 0.004| 0.01| 1   | 1   | 0    | 10      | 9      | 0.0004  | 0.0004 | 0     | 0     |       |       |
| 3.4  | Renewable energy projects (wind, solar)                                             | 100    | 0.004| 0.01| 1   | 1   | 0    | 10      | 9      | 0.0004  | 0.0004 | 0     | 0     |       |       |
| 3.5  | Pollution (residential and industrial effluents, solid waste, agricultural chemicals)| 300    | 0.013| 1   | 1   | 1   | 0.013| 10      | 6      | 0.125   | 0.075  | 0.05  | 2.99  |       |        |
| 3.6  | Oil and gas extraction                                                               | 700    | 0.029| 0.2 | 1   | 1   | 0.006| 10      | 7      | 0.0583  | 0.0408 | 0.0175| 1.05  |       |        |
| 3.7  | Seabed mining                                                                        | 500    | 0.021| 0.2 | 1   | 1   | 0.004| 10      | 8      | 0.0417  | 0.0333 | 0.0083| 0.5   | 0.5   |        |
| Subtotals |                                       | 3950   | 0.165|     |     |     |      |         |        | 4.417   | 2.745  | 1.672 | 26.74 |       |        |
| COMPOSITE TOTAL |                                   | 24,000 | 1   |     |     |     |      |         |        | 4.783   | 3.026  | 1.758 | 100   |       |        |
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