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PERSPECTIVE

The challenges and potential of geogenomics for biogeography and conservation in Amazonia

Abstract

Amazonia has a very high, although still incompletely known, species diversity distributed over a mosaic of heterogeneous habitats that are also poorly characterized. As a result of this multi-faceted complexity, Amazonia poses a great challenge to geogenomic approaches that strive to find causal links between Earth's geological history and biotic diversification, including the use of genomic data to solve geologic problems. This challenge is even greater because of the need for interdisciplinary approaches despite the difficulties of working across disciplines, where misinterpretations of the literature in disparate research fields can produce unrealistic scenarios of biotic-geologic linkages. The exchange of information and the joint work of geologists and biologists are essential for building stronger and more realistic hypotheses about how past climate may have affected the distribution and connectivity among populations, how the evolution of drainage networks influenced biotic diversification, and how ecological traits and species interactions currently define the spatial organization of biodiversity, and thus how this organization has changed in the past and may change in the future. The heterogeneity of Amazonia and the different effects of historical processes over its distinct regions and ecosystems have to be more completely recognized in biogeography, conservation and policymaking. In this perspective, we provide examples of geological, climatological and ecological information relevant to studies of biotic diversification in Amazonia, where recent advances (and their limitations) may not be apparent to researchers in other fields. The three examples, which include the limitations of climate models outputs, the complicated evolution of river drainages and the complex link between species and their habitats modulated by ecological specialization, are a small subsample intended to illustrate the urgency for more integrated interdisciplinary approaches.

1 | INTRODUCTION

Few places have attracted more studies about the historical relationship between landscape evolution and biotic diversification than mega-diverse Amazonia (Cracraft et al., 2020). Yet, the processes that generated so much species diversity through time may never become well known, as deforestation increasingly threatens the whole ecosystem (INPE/PRODES, 2021) (Figure 1). Paradoxically, by losing unique information about the relationship between abiotic and biotic history, we also reduce our capability to predict and manage impacts that could help preserve Amazonia.

Investigations of how Amazon structure and function have changed through time and the likely drivers of those changes require interdisciplinary approaches applied to a very complex system. Both geologic and genomic data can recover past events; thus, the reconstruction of landscape history using geomorphic and paleoclimatic data, and reconstruction of diversification history using genomic data, may be used in tandem to build hypotheses about the coupled evolution of life and Earth that can be reciprocally tested (Baker et al., 2014, 2020; Dolby et al., 2022). Such an approach is at the core of Geogenomics, and its development depends on merging information from many fields, such as paleoclimatology, sedimentology, palynology, geomorphology, systematics, population ecology, population genomics, community ecology, and phylogeography. Making connections among these disparate disciplines is not straightforward, and due to the size and complexity of Amazonia and the explosive increase in new studies, researchers in one field may by necessity overly simplify results from another and consequently generate non-realistic hypotheses or implausible scenarios of past changes in ecosystem structure and function.

Amazonia is essentially a socio-ecological system, and recognizing, valuing, and protecting the knowledge that traditional and indigenous population have about biodiversity is essential both for building better hypotheses about evolution and biogeography and for preserving the biome. Thus, unification of indigenous and academic knowledge is needed in order to study the effects of regional landscape change. Indigenous peoples are key for the environmental and climatic governance of Amazonia, both because their lands cover large extents and because they have accumulated critical knowledge about ecosystem processes. Recent initiatives that aim to combine traditional and academic knowledge have great potential in both generating invaluable knowledge and in partnering with local researchers, who will lead the protection and decision-making processes within their territories in a challenging future (Cabalzar, 2016; Zuanon et al., 2019).

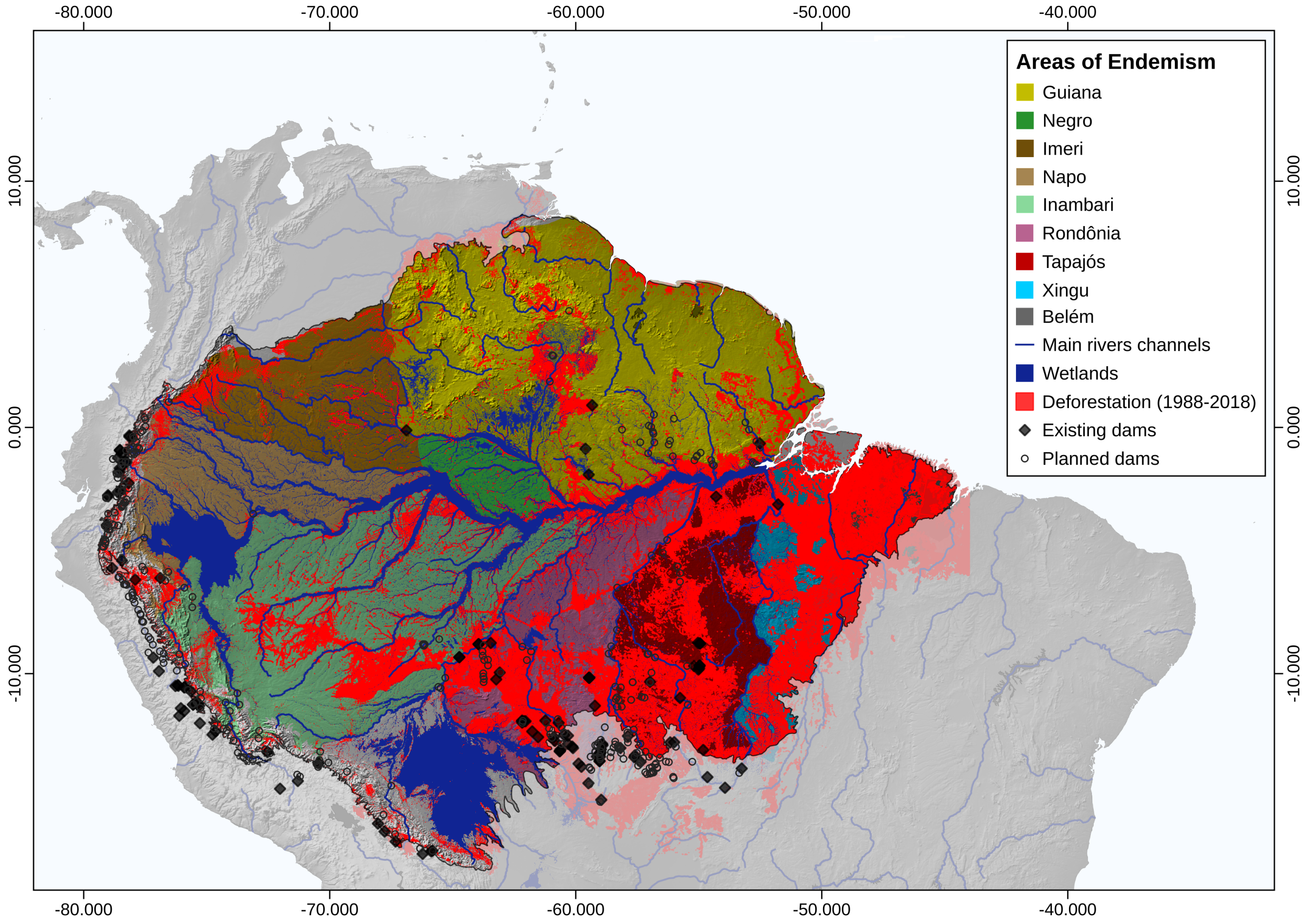

FIGURE 1 Map of northern South America showing the limits of Amazonia as defined by the Amazonian network for georeferenced socio-environmental information, RAISG, (https://www.amazoniasocioambiental.org/en/), the main rivers, wetlands and the delimitation of areas of endemism recognized for upland forest birds and primates (see Cracraft et al., 2020). Deforestation up until 2018 is shown in red. Note that some areas of endemism in southeastern Amazonia have very small areas not affected by deforestation. Deforestation data (2001–2018) from RAISG (https://www.amazoniasocioambiental.org/en/). Wetland distribution from Hess et al., 2015. Existing and planned dams from Latrubesse et al. (2017). Map projection is in universal transverse mercator system (UTM). Latitude and longitude are shown in decimal degrees in vertical and horizontal axes, respectively.

Here we summarize a few select examples of recent advances in knowledge about the geological and climatic history of Amazonia and the evolution of its biota that are common components of narratives about biotic diversification and its causes. Given space limitations, we include a single example of climatic, geological, and ecological information that play an important role in diversification analysis, but where the intricacies of the dynamics may not be broadly apparent to researchers in other disciplines. Our aim is to help build common ground for more realistic and nuanced studies in the future, in order to both understand how highly diverse systems arise and are maintained through time and to provide a baseline for protecting Amazonia from ongoing destruction (Brando et al., 2020).

2 | HOW MUCH DO WE KNOW ABOUT AMAZONIAN CLIMATIC VARIATION AND ITS CONSEQUENCES FOR BIODIVERSITY?

The influence of past climate on Amazonian biodiversity is broadly discussed, often focusing on how changes in the extent of forest or savanna vegetation through time may have affected biological diversification (Haffer, 1969; Wang et al., 2017). Causal relationships between past climates and the evolution of the distinct Amazonian environments can be inferred through reconstructing the historical dynamics of populations of species strongly associated with these specific environments in different regions of Amazonia (Botta et al., 2019). However, important shortfalls in assessing the history of Amazonian biota include the lack of knowledge on current patterns of species diversity and distribution and uncertainties regarding models of past and future climates in the region.

One approach often used to build hypotheses about diversification processes is to extract spatial patterns of Amazonian paleoclimate from global climate model output and to use these reconstructions to infer past species distributions using ecological niche models (Ledo & Colli, 2017). These past distributions may then be used to build population genomic models, including demographic change and connectivity through time. However, paleoclimate model output used for characterizing time slices in the past often differs considerably from inferences derived from actual paleoclimate records, such as speleothems and lacustrine sediment cores, that reconstruct spatial and temporal patterns of paleoclimatic changes within Amazonia (e.g. Baker et al., 2020; Cheng et al., 2013; Wang et al., 2017).

In general, evaluating the past or future of Amazon biodiversity using data from climate models is fraught with uncertainties. A major issue is that general circulation models (GCMs) are currently unreliable in reconstructing precipitation for many places on land (Uhe et al., 2021), including the Amazon where GCMs consistently produce a dry bias (Murphy et al., 2019). The latter problem was first discussed by Li et al. (2006). They analysed all 11 models from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) that simulated rainfall for the A1B emissions scenario. For the observed second half of the 20th century (1950–1999), climatological mean rainfall in the models varied between 2.7 and 5.0 mm day^{-1}, all lower than the observed climatological mean of 5.3 mm day^{-1}. The same 11 models disagreed on the sign of projected precipitation change, simulating increased (5 models), decreased (3 models) or nearly constant (3 models) rainfall for the second half of the 21st century. More recently, Parsons (2020) analysed 32 models from IPCC AR5 and 22 models from IPCC AR6 (IPCC 2021) and, while properly urging caution, he concluded that the "new generation of models shows better agreement that most of the Amazonian basin will receive less future rainfall." Yet, his own analysis belies the ability of this newer generation of models to accurately simulate historical (1950–2000) rainfall. Even for the season (ONDJFM) and region ("eastern Amazonia" but including large areas outside of Amazonia) chosen because of their stronger coupling of precipitation to ENSO forcing, the historical simulation of the climatological seasonal rainfall ranged from 239–1417 mm (mean 890 mm) for AR5 and 468–1255 mm (mean 892 mm) for AR6, again much lower than the observed mean of 1230 mm (Parsons, 2020). While there is better agreement in the sign of predicted future change among AR6 models compared to that found by Li et al. (2006), indicating possible decreased precipitation by the end of the 21st century in this region and in this season, particularly in the drastic SSP3-7.0 emission scenario, a significant (but unquantifiable) portion of that trend is driven by scenario-prescribed widespread deforestation (Parsons, 2020; in particular, their supplemental figure 7). Cook et al. (2020, their figure 2) found that for less drastic emissions scenarios, AR6 model simulations of precipitation were not robust over large areas of Amazonia for most seasons. Also, while Ukkola et al. (2020) found a strong tendency for increased drought (i.e. rainfall deficit), they report only a statistically insignificant decrease of 7% in mean annual precipitation across Amazonia by the end of the 21st century in AR6 model ensembles under the drastic emissions scenario (RCP 8.5).

In short, we conclude that the current generation of GCMs are unreliable for hindcasting precipitation in the Amazon for the instrumental era (1950-present) and thus must be considered unreliable for accurately hindcasting precipitation for the pre-historic past and for accurately forecasting the global warming future. It is necessary to understand the limitations and uncertainties of GCMs and of various different model intercomparison methods (Uhe et al., 2021), whether for hindcasting or forecasting, and these limitations must be explicitly recognized in studies that build or test hypotheses about biotic diversification. Within Amazonia, information about past landscapes based on local data, such as speleothem, sedimentological, dendrochronological and palynological records, although available for very few locations, is more reliable than currently available GCM output.

3 | EVOLUTION OF RIVER DRAINAGES AND "RIVERINE BARRIERS" THROUGH TIME

Rivers are conspicuous biogeographic features of the Amazonian lowlands, often bounding biotic distributions, thus the "riverine barrier hypothesis" (Wallace, 1852) is invoked in many studies of Amazonian biogeography. These studies all-too-often conflate pattern and process. For example, the pattern of endemism found for some vertebrate groups, such as birds and primates associated with upland forests, in which areas of endemism are bounded by large Amazonian rivers (e.g. Ayres & Clutton-Brock, 1992; Boubli et al., 2015; Cracraft, 1985; Haffer, 1974; Maximiano et al., 2020; Wallace, 1852) (Figure 1), may not be found for other organisms, such as plants and insects (Dambros et al., 2020; Nazareno et al., 2019a), which have their own distinct ecological traits and dispersal modes. Even for those organisms where such a river-bounded distribution pattern exists, allopatry caused by the "origin" of the river is not necessarily the unique explanatory process responsible for generation of the current biotic distribution (Coyne & Orr, 2004; Cracraft et al., 2020), and further analyses of the diversification process are needed to test this causal relationship.

When biologists think about the "origin" of a river they may envision a different scenario of change than geologists studying the same set of events. In biodiversity literature, riverine barrier hypotheses are often put forth without considerations of the geological mechanisms of river origins and evolution, how different habitats are distributed along Amazonian rivers, and the consequences of changes in the drainage system to the organisms that occur in the distinct habitats created or subdivided by rivers (Pupim et al., 2019; Thom et al., 2020).

Moreover, uncertainties about the geologic history of Amazonian drainages often are not translated in an accessible way for non-geologists. As an example, paleogeographic reconstructions of past configurations of the Amazon basin are often presented without depictions of alternative scenarios or robust discussions of uncertainty (e.g. Albert et al., 2018; Hoorn et al., 2010). Many studies treat the origin of the transcontinental Amazon River as synonymous with the origin of "modern Amazonia", whereas it is certain that the landscapes associated with the Amazon rivers and their floodplains continued to change and evolve long after transcontinental drainage was established (Bicudo et al., 2019; Goldberg et al., 2021; Pupim et al., 2019) and will continue to change into the future. For example, the geological scenario of an old origin of the transcontinental drainage with little subsequent change in the drainage pattern since then would originate biological diversification hypotheses in which species whose distributions are currently bounded by the main Amazon rivers would have been isolated from their neighbours for a long time (ca. 7–10 myr, according to Figueiredo et al., 2009; Hoorn et al., 2010). However, most species associated with upland non-flooded habitats and currently bounded by large rivers studied so far are much younger (Boubli et al., 2015; Nazareno et al., 2019b; Ribas et al., 2012, 2018; Silva et al., 2019). Moreover, divergence dates often vary from one pair of sister species to the other across the same river (Naka & Brumfield, 2018). If, on the other hand, rivers and floodplains are very dynamic, and their positions are continuously changing due to sedimentation processes, avulsions, and river capture events (Ruokolainen et al., 2019), how can they still represent common distribution limits for so many taxa? Many geologists and biologists are presently investigating the mechanisms that control the dynamism of the Amazonian drainage and how it affected biotic distributions during the period when current Amazonian species were diversifying (Barbosa et al., 2021; Luna et al., 2022; Pupim et al., 2019; Silva et al., 2019; Thom et al., 2020).

The nuances of drainage evolution need to be explicitly included in tests of riverine barrier hypotheses. For example, the changing fluvial dynamics throughout the history of a meandering river in the sedimentary Solimoes Basin of western Amazonia may have mostly affected its floodplains, with occasional changes in the connectivity of upland forest taxa being controlled mostly by precipitation (Goldberg et al., 2021; Pupim et al., 2019). On the other hand, river capture events on the Precambrian shields, or associated with changes in the water base level, were more able to alter connectivity for larger regions of both aquatic and terrestrial environments through river capture events and reconfiguration of the sub-drainages (Dagosta & Pinna, 2017).

Another important characteristic that distinguishes the roles of different Amazonian rivers as barriers to dispersal for upland-forest-associated organisms is their geographic position, which may or may not be entirely within upland humid forest. The presence of forest along the headwaters of a river (today or in the past) is crucial for determining if that river could serve as a dispersal barrier for forest-associated populations (Ribas et al., 2012; Weir et al., 2015). Yet, a river network evolves far more often through a series of connections and disconnections among its many channels than by whole rivers originating at a specific moment in time. Thus, changes in connectivity between portions of the river channels may generate configurations that isolate populations effectively for specific and unique periods of time. While many studies of biological diversification try to elucidate the "relative contribution" of drainage evolution and paleoclimatic change to current biogeographic patterns, often both drainage and climate changed and influenced one another during the same periods of time, with spatially distinct effects across the huge Amazon basin, depending, among other things, on the underlying geological formation (Goldberg et al., 2021; Pupim et al., 2019; Thom et al., 2020).

Even when gene flow does occur across a river barrier, other factors, including population size, individual recognition and fitness of hybrids may influence the persistence of the hybridization signal through time. The few available studies suggest that even when hybridization occurs, it may be restricted to narrow regions and often fails to disrupt the prior pattern of species distribution and genetic variation (Weir et al., 2015). With so many possible changes in the landscape and possible outcomes of barrier crossing events, the finding of congruence should be expected to be rare (Papadopoulou & Knowles, 2016), and when it does occur it represents an important opportunity to unveil the complex relationship between Earth history and the origin of species. The absence of generalized congruence, thus, is not, in itself, evidence of uncoupled Earth and biotic history.

4 | SPECIES TRAITS AND ECOLOGICAL SPECIALIZATION MODULATE THE RESPONSE OF BIODIVERSITY TO LANDSCAPE EVOLUTION

Amazonian habitats may be roughly divided into non-flooded or seasonally flooded (Figure 1) and into open-canopy or closed-canopy (Ribas & Aleixo, 2019). Different assemblages of species are associated with each habitat type (Laranjeiras et al., 2021; Oliveira-Filho et al., 2021). This heterogeneity is itself difficult to characterize, yet vital for current impact assessment and conservation planning (Silva et al., 2005). Estimating how these patterns changed in the past due to historical changes in landscape and how they evolved into the complex mosaic that we see today is a formidable scientific challenge, one that provides indispensable information for understanding the future of Amazonia.

The history of each taxon and its resilience through time are deeply linked to the kinds of environments it occupies (Barbosa et al., 2021). Many Amazonian taxa are restricted in distribution, occurring only in a set of specific habitats or in a specific geographical region (Dambros et al., 2020; Oliveira-Filho et al., 2021; Wittmann et al., 2013), contributing to the high diversity and endemism associated with specific areas and habitats. However, because the heterogeneity of lowland Amazonian habitats has been underappreciated, and the taxonomy of Amazonian organisms is still very incomplete, many taxa have been mistakenly considered widespread and generalist, and, consequently, resilient to landscape change (Cracraft et al., 2020).

An important consequence of the distinct habitat associations of species is that the same landscape change may lead to increased connectivity for some groups and isolation for others (Pupim et al., 2019; Thom et al., 2020). For example, patterns of historical connectivity among populations that inhabit upland rainforest habitats are influenced by the changing courses of the major lowland rivers and their associated floodplains, and also by prominent topographic and habitat discontinuities, such as open savannah vegetation, mountain ranges and sandy soils (Capurucho et al., 2020; Cracraft et al., 2020; Nazareno et al., 2017, 2019a), whereas connectivity within floodplain habitat specialists is affected by sedimentation patterns that govern cycles of aggradation and erosion and thus the availability of the distinct floodplain habitats through time (Barbosa et al., 2021; Luna et al., 2022; Nazareno et al., 2021; Pupim et al., 2019; Thom et al., 2020).

In some groups, such as birds and plants, the contrasts in diversity patterns of taxa with distinct habitat affinities have been clearly shown, both in community composition and genomic studies (Capurucho et al., 2020). Whereas several species associated with upland habitats have clear genomic structure delimited by the rivers (Nazareno et al., 2019b; Silva et al., 2019), floodplain associated taxa have their connectivity facilitated by the river channel and associated floodplains (Nazareno et al., 2021; Thom et al., 2020). Yet, many biogeographic studies look for congruence and end up dismissing a relationship between Earth history and biotic diversification when congruence is not found. Unique ecological traits of individual species that determine their habitat affinities, coupled with the complex and dynamic habitat heterogeneity of Amazonia, may have resulted in different spatial and temporal patterns in the diversification of co-existing lineages in response to past landscape changes (Naka & Brumfield, 2018; Silva et al., 2019; Thom et al., 2020). Thus, understanding this link between species and their preferred habitat is essential for building and testing hypotheses about landscape history and diversification. So too is the understanding of how specific geological processes, such as river incision, affect the distribution of and connectivity among different Amazonian habitats (Pupim et al., 2019).

An important source of uncertainty in estimating both past potential distributions and future responses of species to climatic change is our lack of knowledge about ecological traits that define exactly how each species is affected by changes in water availability and temperature (Esquivel-Muelbert et al., 2017). Subtle changes in forest structure related to climatic change may affect each species differently, with consequences for its overall distribution, abundance, phenotypic traits and thus for the connectivity within and between its populations (Arruda et al., 2017; Stouffer et al., 2021). Although occurrence data, if available in sufficient detail, may account for such subtleties, we often lack knowledge of those detailed environmental variables that interact with climatic variables to capture nuances about distinct Amazonian habitats, such as the duration of annual seasonal flooding and soil types at each locality (Figueiredo et al., 2018; Zuquim et al., 2019). Records from permanent forest monitoring plots in Amazonia show that forest composition responds to climate change, with dry-adapted species increasing in abundance with intensification of the dry season (Esquivel-Muelbert et al., 2019). This reinforces the observation that edaphic conditions are key factors driving the distribution of the distinct floristic units in Amazonia, often leading to sites with similar vegetation occurring in geographically distant regions (Oliveira-Filho et al., 2021; Tuomisto et al., 2019). Even within the dominant non-flooded *terra firme* forests, there is considerable environmental heterogeneity (Tuomisto et al., 2019). These results show that estimating the effects of climate change over this complex mosaic of vegetation types will depend on accumulating knowledge about the traits that define how vegetation responds to climate and how animals respond to vegetation change. Importantly, biodiversity response to climatic change often occurs on an extended time scale, and baseline information obtained through permanent monitoring is essential to detect it.

5 | THE FUTURE OF AMAZONIAN BIOGEOGRAPHY

Within the immense region that we call Amazonia, past climate and geomorphology have varied in spatially heterogeneous ways. Rivers of the western region, with high sediment loads, changed their courses in different ways when compared to rivers flowing on hard substrates of the shields in the eastern part of the region. Ignoring the complex spatio-temporal variability of past climate or of the geomorphology driving drainage evolution may hinder progress in understanding Amazonian biotic diversification.

Lack of detailed information on the natural history of species whose distributions and population dynamics we are trying to infer in time and space presents another challenge. Even the basic distinction between seasonally flooded versus upland (never flooded) habitats is often not clear in threat assessments and deforestation mapping, even though these distinct habitat types and their associated biota have very different spatial distribution, respond differently to climatic extremes, and recover differently from fires (Flores et al., 2017; Melo et al., 2021). For example, species that today occur in upland, non-flooded *terra firme* habitats may have relied historically on extensive habitat available throughout Amazonia to track appropriate climatic conditions within the mosaic of distinct upland forest patches. This may be why most populations of upland forest birds studied to date show genetic signals of past population size changes (Silva et al., 2019). However, these non-flooded forest habitats are becoming more fragmented by anthropogenic interference (Figure 1), and the ability of populations to track suitable habitat in response to climatic variation is declining quickly in some regions of Amazonia. This, coupled with accelerated climatic change, is often not considered in assessing threats to biodiversity. Information on genomic diversity, population structure, and population demography, coupled with an understanding of the historical relationship of each unique population and its preferred environment, has to be incorporated into studies estimating extinction risk, especially in southeastern Amazonia (Figure 1). Through geogenomic analyses it is possible, for example, to identify unique evolutionary lineages that have gone through strong bottlenecks in the past in response to climate change, and which are currently confined to highly deforested interfluvia.

The phylogenetic structure of current local communities also reflects differential dispersal, habitat availability, and local extinctions, which are related to historical habitat stability (Gerhold et al., 2018). Previous studies using published range maps and phylogenies of Amazonian birds suggest that community phylogenetic structure reflects differential habitat histories across Amazonia (Bicudo et al., 2019; Crouch et al., 2018). However, currently available range maps and taxonomically incomplete phylogenies hinder a more realistic approach for investigating the effects of past Amazonian landscapes on the current organization of biotic diversity. Thus, improving these datasets through continued taxonomic and systematic reviews combined with standardized sampling of local communities is key for informing predictions about the impacts of future climate change on community composition and net diversity loss (Blundo et al., 2021; Maximiano et al., 2020; Pancost, 2017; Stouffer et al., 2021). Such predictions will be fundamental for the future of Amazonia. Fostering sustainable development in Amazonia needs to include both better-informed planning at the administrative level and successful partnerships between often-disparate research disciplines and knowledges (Cabalzar, 2016).

New biological and geological investigations are generating increasingly nuanced narratives of historical trajectories in space and time. Incorporating this new ecological and geological information obtained from distinct habitats within Amazonia into diversification hypotheses will take time and collaboration across disciplines and cultures to minimize faulty generalizations based on sparse data or incomplete understanding of complex dynamics. Spatially and temporally restricted hypotheses might be more effective in advancing understanding, considering the limited information still available for the large and complex region of Amazonia. These efforts should enable future integrated studies to generate more refined and realistic hypotheses about the past and the future. Examples of questions that would benefit from such a combination of geologic and genomic data from Amazonia are: (1) the molecular ages of river barriers (e.g. birds, insects, plants) and river connections (e.g. fishes), coupled with information on species' habitat affinities, can be used to characterize the temporal evolution of specific river channels; (2) refined reconstructions of past demographic histories of populations using whole genome data combined with detailed information of species—habitat interactions may be used to constrain reconstructions of variation in habitat availability through time; (3) molecular ages of niche-conservative taxa in Andean highlands are indicative of the timing of the uplift of those highlands, when coupled with information on habitat changes due to climate variability; (4) ages of Andean dry valley taxa can be used to date the age of uplift of the ranges that are responsible for orographic effects. Several recent studies provide examples of the need and the promise of effective integration of new geologic and genomic data in unravelling combined evolutionary patterns and processes.

6 | FINAL REMARKS

We suggest that the study of Amazonian bio and geo diversity needs to be seen as a truly interdisciplinary endeavour. Both biologists and geologists have to expand their knowledge of each other's fields, as the complexity of the system does not allow for simple, single-discipline, approaches. Relying on large and poorly curated datasets that summarize current knowledge of Amazonian species' taxonomy and distribution may lead to unrealistic meta-analyses and to general conclusions that may not contribute much to actually understanding the system and its history. In fact, one main challenge for Amazonian biogeography and conservation is the fact that much basic knowledge about species identities, limits, distributions, and ecological characteristics is still under construction (Blundo et al., 2021; Damasco et al., 2021; Lees et al., 2020), as is the knowledge about geomorphologic and climatic history (Baker et al., 2020; Cracraft et al., 2020). As such we seem to be at a challenging point in which the test of complex hypotheses about how biotic and abiotic factors influenced each other through time needs to advance concomitantly with the description of current biodiversity and the better understanding of basic Earth history processes.

Understanding the relationships between species and their habitats is essential in this endeavour. Amazonian indigenous and traditional populations hold a vast knowledge about this subject. Indigenous lands occupy almost 25% of Brazilian Amazonia and include the better-preserved areas (Walker et al., 2020). Indigenous and traditional populations use and maintain the natural resources, having developed complex calendars, or modes of life, based on species traits and the annual cycle of flooding that characterizes Amazonia (Cabalzar, 2016). Partnerships with indigenous and local researchers are an essential part of constructing more nuanced views of how Amazonia changes through time and how large scale anthropogenic impacts affect complex natural processes (Cabalzar, 2016; Zuanon et al., 2019).

KEYWORDS

biodiversity, diversification, drainage, Neotropics, paleoclimate, rivers, sedimentation

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CONFLICT OF INTEREST

The authors claim no conflict of interest.

DATA AVAILABILITY STATEMENT

No new data were generated for this perspective.

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BIOSKETCH

Camila C. Ribas is interested in biogeography and conservation in the Neotropics, with special focus in Amazonian birds.

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