EBP-Colombia and the bioeconomy: Genomics in the service of biodiversity conservation and sustainable development

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The 2016 Peace Agreement has increased access to Colombia's unique ecosystems, which remain understudied and increasingly under threat. The Colombian government has recently announced its National Bioeconomic Strategy (NBS), founded on the sustainable characterization, management, and conservation of the nation's biodiversity as a means to achieve sustainability and peace. Molecular tools will accelerate such endeavors, but capacity remains limited in Colombia. The Earth Biogenome Project's (EBP) objective is to characterize the genomes of all eukaryotic life on Earth through networks of partner institutions focused on sequencing either specific taxa or eukaryotic communities at regional or national scales. Colombia's immense biodiversity and emerging network of stakeholders have inspired the creation of the national partnership "EBP-Colombia." Here, we discuss how this Colombian-driven collaboration between government, academia, and the private sector is integrating research with sustainable, environmentally focused strategies to develop Colombia's postconflict bioeconomy and conserve biological and cultural diversity. EBP-Colombia will accelerate the uptake of technology and promote partnership and exchange of knowledge among Colombian stakeholders and the EBP's global network of experts; assist with conservation strategies to preserve Colombia's vast biological wealth; and promote innovative approaches among public and private institutions in sectors such as agriculture, tourism, recycling, and medicine. EBP-Colombia can thus support Colombia's NBS with the objective of sustainable and inclusive development to address the many social, environmental, and economic challenges, including conflict, inequality, poverty, and low agricultural productivity, and so, offer an alternative model for economic development that similarly placed countries can adopt.

biological conservation | ecosystem management | green economy

Colombia is ranked as the second most megadiverse country on Earth. This includes an estimated 7,385 vertebrates, 20,647 invertebrates, 30,736 plants, and 1,637 fungi, with many endemic species (1). Decades of armed conflict, limited infrastructure, and a lack of financial resources commensurate to this substantial concentration of planetary biodiversity have left Colombia's ecosystems comparatively inaccessible, intact, and understudied. Yet, with the historic 2016 Peace Agreement (Fig. 1), vast tracts of the megadiverse Colombian landscape are opening to both biodiversity research and economic activities (2). Since the Peace Agreement, extractive industries (timber, mining, petroleum) and agriculture (particularly cattle ranching) have been encroaching on newly accessible biodiverse ecosystems at an accelerating rate, threatening the country's ecology while potentially providing quick financial returns that stimulate Colombia's economy (3). With an estimated 42.5% of the population living in poverty, especially in rural areas, the country is now forced to make challenging decisions about how best to balance the very real

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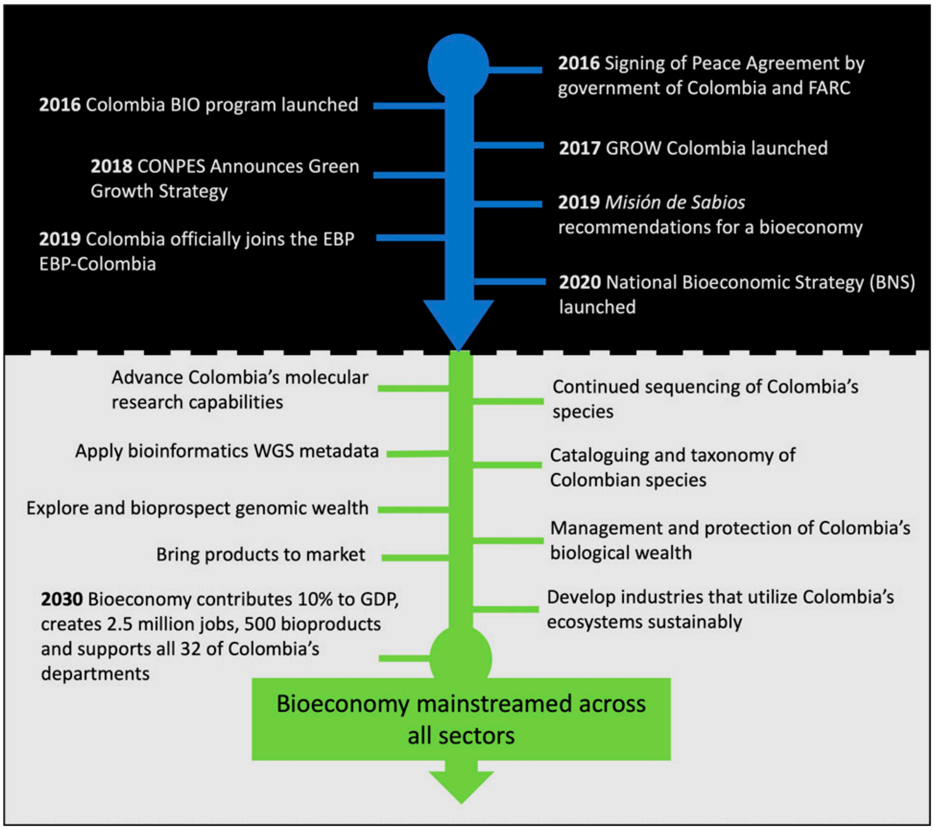

Fig. 1. Time line of events leading up to the launching of EBP-Colombia in 2019 and the NBS in 2020 (black background), beginning with the signing of the Peace Agreement in 2016. The projected goals and achievements of the EBP-Colombia partnership and NBS leading up to 2030 are shown (gray background). FARC, Revolutionary Armed Forces of Colombia.

need for economic development to increase the standard of living and alleviate social ills, such as inequality and conflict, while also conserving its remarkable biodiversity (4).

Transitioning toward a bioeconomy, in which wealth is generated through innovative economic activities that utilize renewable biological resources equitably and responsibly without negatively impacting biodiversity, offers a viable solution to sustainably meet the economic growth gap (5, 6). In 2018, 41 countries had adopted strategies or policies designed to develop or expand their bioeconomies, with more set to follow (5). The World Business Council for Sustainable Development has estimated the bioeconomy will have a global economic potential of $7.7 trillion by 2030 (7). The Colombian government has recognized that Colombia, with its significant biological wealth, is uniquely positioned to capitalize on this opportunity and provide a blueprint for sustainable development that other emerging economies can emulate (6, 8). In this paper, we discuss how the formation of a national, Colombia-led Earth Biogenome Project (EBP) partnership, dubbed "EBP-Colombia" (Fig. 1), will complement and accelerate the nation's bioeconomic ambitions.

Colombia's Bioeconomic Vision

In 2020, the Colombian government launched its National Bioeconomy Strategy (NBS) (Fig. 1), a long-term, postconflict, bioeconomic development plan focused on evaluating, conserving, managing, and sustainably using Colombia's valuable biological resources (6). The NBS brings together three key government initiatives central to the country's bioeconomic landscape: Colombia BIO (https://minciencias.gov.co/portafolio/colombia-bio), the Misión de Sabios (https://minciencias.gov.co/mision_sabios), and the National Council for Economic and Social Policy's (Consejo Nacional de Política y Economía Social [CONPES]; https://www.dnp.gov.co/CONPES) ambitious Green Growth Policy (9), published in 2018 (Fig. 1).

The Colombia BIO program was launched in 2016 and uses biological expeditions to increase knowledge and understanding of Colombia's species, with a particular emphasis on remote areas with large information gaps and taxonomic groups for which there are very few records (10). So far, US$76 million have been invested in the Colombia BIO program since 2015, with 37 expeditions logging >500,460 biodiversity records in the Colombian Biodiversity Information System (https://sibcolombia.net/) (11). This includes 206 species possibly new to science and 200 species endemic to Colombia. These extensive research outputs have mobilized over 1,000 researchers and engaged 146 national institutions and 38 international institutions (11).

The Misión de Sabios ("Mission of the Wise") is a panel of national and international experts in sciences and humanities (currently numbering over 40) assembled by the government. The mission is charged with developing long-term scalable, replicable, and sustainable strategies and policy proposals for the advancement of science, technology, and innovation while addressing social issues, such as poverty and inequality (12). In 2019, the mission recommended that the bioeconomy should contribute at least 10% of gross domestic product (GDP) and generate at least 100,000 jobs by 2030 (12).

CONPES is the highest national governmental planning authority, advising on all aspects related to economic and social development. In its 2018 Green Growth Policy, CONPES defined a bioeconomy as an "economy that efficiently and sustainably manages biodiversity and biomass to generate new value-added products, processes and services based on knowledge and innovation" (9). The policy set out three bioeconomy targets embracing this definition for 2030: 1) to increase the number of bioinnovative companies by 86%, 2) to increase the number of spin-offs and start-ups by 180%, and 3) to increase by 19% the production of goods and services by biocompanies (9). The policy also identified a range of priority sectors for development as part of the bioeconomy, including cosmetics, chemicals, pharmaceuticals, health care, agriculture, food, and beverages (9).

The NBS will build on the momentum of these three initiatives between now and 2030 in five ways. First, it will support the Colombia BIO program to further explore biodiversity and quantify ecosystem services. This will assist conservation efforts as well as the development of bioeconomic activities, such as bioprospecting, understanding and harnessing traditional knowledge, and developing ecotourism (13). Second, it will create a "biointelligent" Colombia, focused on "omics" fields, data science, pharmaceuticals, biotechnology, biosimilars, and phytotherapeutics (8, 13). Third, it will move to more productive and sustainable agriculture by adopting precision farming, cultivating new crop varieties, bioinputs, conscious consumption, and healthy food. Fourth, it will assist the transition to a circular economy utilizing biomass and green energy to move toward a zero-waste model, with biorefineries, biofactories, and bioenergy. Fifth, it will focus on health and wellness by using personalized and translational medicine (13).

By 2030, the NBS aims to meet the Misión de Sabios's goal of a 10% contribution to Colombia's GDP and surpass their employment goal by creating 2.5 million jobs, as well as developing over 500 bioproducts, while engaging all of Colombia's regional departments (11). This will also directly contribute to the country's efforts to meet the United Nations sustainable development goals (8).

Colombia already has demonstrated bioeconomic successes, with companies such as Labfarve, Neyber, and Biocultivos among others feeding into biofuels, cosmetics, medicines, and biotechnology (14). However, the further molecular exploration of Colombia's vast biological wealth will be key to achieving the targets of the NBS. Whole-genome sequencing (WGS), high-throughput molecular research, metabolomic studies, and big data mining using machine learning are key components of new innovations in biotechnology globally (15). These feed back into multiple sectors, including conservation, agriculture, medicine, and pharmaceuticals, all included in the NBS (15, 16). The considerable economic and social benefits produced by molecular research and exploration of genomes are evident in endeavors such as the Human Genome Project. This is estimated to have created returns on investment of $178 for every public dollar spent on the project, generating over $1 trillion only a decade after the project ended and benefiting human health and welfare (17). However, the uptake and application of molecular tools to Colombia's biodiversity remain challenging, limited by country-wide deficits in molecular infrastructure and research, including a lack of funding, technical capacity, and poorly developed supply chains. These challenges are reflected in the comparatively small contribution of Colombian genomics to global databases (1).

EBP-Colombia

In 2019, Colombia officially joined the EBP through the creation of a mutually beneficial EBP-Colombia (Fig. 1). With its significant fraction of planetary biodiversity, Colombia is a vital player in the EBP's goal to sequence all eukaryotic species (16). Prior to EBP-Colombia, projects and initiatives operated in country using a bottom-up approach to contribute outputs to the EBP through international collaborations. For instance, the capacity-building initiative GROW-Colombia (https://www.growcolombia.org/) is in the process of sequencing cacao species and other endemic crop varieties alongside animals of conservation concern, such as the iconic Andean bear (*Tremarctos ornatus*). Colombian research grants are also contributing their findings to the EBP, such as the sequencing of the capybara (*Hydrochoerus hydrochaeris*) (18).

Such projects have raised the profile of the country's molecular biodiversity research nationally and internationally and spotlighted its untapped genomic wealth (1). In addition, they have established a collaborative Colombian community of stakeholders developing molecular research capacity, driving the political will for EBP-Colombia. This research network includes the Ministry of Science, Technology and Innovation (also known as MinCiencias), Colombia's government agency in charge of developing science policy and promoting research; universities, such as Universidad de los Andes and University National; government-supported biodiversity research institutes, such as the Instituto de Investigación de Recursos Biológicos Alexander von Humboldt and Instituto Amazónico de Investigaciones Científicas; and international organizations, such as the International Center for Tropical Agriculture, the Natural History Museum of London, and of course, others in the extensive global EBP network.

The EBP-Colombia consortium will expand and consolidate this network, ensuring the continued efficient and collaborative genomic exploration of Colombia's biological wealth in Colombia, with international inputs from the EBP's experts. EBP-Colombia will stimulate further equitable synergies to sequence eukaryotic life between government agencies, local stakeholder groups such as public and private institutions, indigenous communities, nongovernmental organizations, academics, and the EBP's extensive global network of genomics experts and so, is auspiciously timed to contribute to the NBS.

EBP-Colombia's Contributions to the NBS

EBP-Colombia's activities subscribe to the three EBP goals outlined in its Memorandum of Understanding (16, 19). These are 1) to revise and reinvigorate our understanding of biology, ecosystems, and evolution; 2) to enable the conservation, protection, and regeneration of biodiversity; and 3) to maximize returns to society and human welfare (19). Already, EBP-Colombia is meeting these goals and in doing so, directly and indirectly complementing and contributing to the NBS. Here, we discuss how current EBP-Colombia activities meet the EBP goals and can bolster Colombia's bioeconomic trajectory.

1) Revise and Reinvigorate Our Understanding of Biology, Ecosystems, and Evolution. The accurate taxonomic identification and cataloguing of species are integral to managing biological resources sustainably. EBP-Colombia is complementing existing efforts to advance understanding of Colombia's biodiversity and ecosystems, such as the Colombia BIO program. WGS of samples collected on the Colombia BIO expeditions adds a molecular lens to cataloguing efforts (e.g., ref. 18); this can be used to identify cryptic species, as demonstrated by recent analysis of crocodilian genomes (20, 21). Beyond the fundamental application of taxonomy, analysis of genomes can reveal evolutionary adaptations, species origins, and introgression and resolve complex phylogenies (22). Molecular analysis will also advance understanding of how species are adapted to their environment and so, our knowledge of Colombia's ecosystems and their effective management (23).

The reference genomes generated from tissue sequencing of collected samples will facilitate the shotgun sequencing of museum voucher specimens, thereby unlocking the vast genomic information preserved in the historical collections in Colombia's zoos, museums, and universities (24, 25). This is already taking place through the Andean Bear Project, and technological advances mean that many museum specimens may be of suitable quality for WGS (26). Colombia's extensive natural history collections can then provide valuable historical baselines for species genomics and comparisons with current populations (25).

In one of EBP-Colombia's first official projects, genomics are being used to aid the sustainable use of a traditional food source and involving local communities. The bivalve, "piangua" (*Anadara tuberculosa*), is a locally important food for communities along Colombia's remote Pacific Coast. EBP-Colombia is currently developing a chromosome-level reference genome and a metagenomic characterization of its holobionts using highly portable nanopore devices, providing real-time sequencing in the field and obviating the need for exporting biological material or importing digital sequence information. The Piangua Project is engaging local communities in the execution of the project and will work with them to plan how best to manage this resource.

2) Enable the Conservation, Protection, and Regeneration of Biodiversity. Because effective management and conservation require us to identify and delineate species and understand their range and historical population size, WGS has huge practical benefits for optimizing conservation measures (16, 20). The latest genomic technologies can be applied to any organism, allowing conservation geneticists to characterize variation within species, individuals, and populations, including functional genomic diversity and historical demography with unprecedented detail (22, 27). Undoubtedly, those genomes sequenced by the EBP-Colombia network will produce outputs that can be used to ensure the NBS's sustainability and conservation credentials.

Reference genomes are used to reveal the molecular genetic basis of deleterious as well as adaptive mutations and facilitate marker-assisted breeding programs. The assembling of a chromosome-level reference genome for the Andean bear, a threatened icon of Colombian biodiversity, will reveal runs of homozygosity across the genome. The museum samples are supplemented by 139 fecal samples collected from across the bears' geographic range in Colombia plus blood samples collected from wild individuals. The results of this work will feed back into management and conservation measures, such as understanding the connectivity between bear populations and how these can be managed effectively to optimize genetic diversity and the conservation of this species. As demonstrated by Johnson et al. (23), similar work on another charismatic large mammal, the koala (*Phascolarctos cinereus*), has yielded insights that have advanced understanding of its ecology in terms of diet, reproduction, and vulnerability to diseases and fed directly into conservation and management with the establishment of corridors to reduce inbreeding.

Another EBP-Colombia project, Alas, Cantos y Colores (Wings, Songs and Colors; https://minciencias.gov.co/colombia-bio/alas-cantos-y-colores), is currently resurveying sites visited by the American Museum of Natural History in 1912 to collect tropical bird specimens. Genetic comparison of 1912 museum specimens with samples collected from birds during the resurvey, including *Heliangelus exortis* (tourmaline sunangel), *Myioborus ornatus* (golden-fronted whitestart), and *Atalpetes fuscoolivaceus* (dusky-headed brush finch), will provide a unique perspective on how tropical bird genomes have responded to land use, climate, and other broad changes to the Colombian landscape over 109 y (3). Conservation genomic work on each of these three bird species will be supported by a chromosome-level genome assembly now in development.

EBP-Colombia is not exclusive to the acquisition of whole genomes; many of the workflows will include partial sequencing DNA, such as barcodes or mitochondrial DNA (mtDNA) made possible by the establishment of comprehensive genetic resource bases and sequencing capacity. These shorter sequences are much easier to obtain than WGS and have diverse applications. Already, GROW-Colombia has started a project looking for cost-effective, scalable solutions for sequencing fish mtDNA from existing tissue collections in order to create a catalog of barcodes. This will enable the uptake of environmental DNA for rapid ecosystem monitoring (i.e., via metabarcoding), especially in aquatic environments, which remain poorly understood (28). In a country where traditional aquatic surveys are often unviable, these molecular sentinel tools will reveal biological communities on an unparalleled scale and can contribute to wider global initiatives (e.g., eBioAtlas; https://ebioatlas.org/) (28). Such tools can be used to ensure the sustainability and ecological integrity of not just the NBS but also, other sectors, such as extractive industries, and ensure that impacts are appropriately monitored and mitigated.

3) Maximize Returns to Society and Human Welfare. If the Human Genome Project demonstrated the return on investment for sequencing one species (17), what are the returns on investment when sequencing some 10% of eukaryotic life? First, the genomic capacity building by EBP-Colombia necessary for the two previous EBP goals mentioned will equip Colombian institutions with the technological expertise and access to tools to answer this question. This human capital is a profound and necessary contribution of EBP-Colombia to Colombia's bioeconomic ambitions. Through equitable, collaborative projects with strong Colombian representation from local institutions and input from the global EBP network, EBP-Colombia will continue to train future generations of Colombian genomicists who are engaged both with society and with the government.

Of course, training scientists without also providing access to data generation and computational tools would leave them with zero "capacity." EBP-Colombia will, therefore, encourage the use of modular, portable, long-read sequencing devices (currently offered only by Oxford Nanopore Technologies) as these allow in-country sequencing and analysis as demonstrated by the Piangua Project and the fish mitochondrial genome sequencing project. The technical and operational know-how of high-throughput and WGS alongside associated computational tools is equipping a cohort of Colombian researchers with the skills and expertise required to record and explore their country's biological wealth. We expect that these portable tools will pave the way for more expensive high-throughput molecular sequencing capacity in Colombia as demand increases.

This development of homegrown talent, access to technology, and open-access reference genomes will transcend the eukaryotic aspirations of the EBP and benefit biotechnology and innovation in public and private institutions, fulfilling the NBS's goal for a biointelligent Colombia. Colombia will thus be ready to conduct genomic surveys on its thousands of plant, vertebrate, fungal, and protist species, facilitating the discovery of novel molecules, fibers, and proteins with human health benefits and industrial applications (6, 15). In addition, molecular characterization is often a prerequisite essential to bringing discoveries to market both for scaling production and downstream processing into value-added products, both goals of the NBS.

EBP-Colombia's contributions to a knowledge base and reference database of Colombia's genetic resources can be effectively mined to provide solutions to a range of current and future challenges, such as food and nutritional security through genetic improvement strategies (1, 29). This is especially true for crops endemic to Colombia, like those the GROW-Colombia project is sequencing. For cacao, the uptake of cadmium is a major barrier to export; however, the sequencing of wild species, such as *Herrania* spp. and *Guazuma ulmifolia*, is expected to lead to crop improvements that reduce cadmium uptake to levels permissible for export to new markets and more resilient strains. Ultimately, genetic improvements such as these ultimately benefit society at each step along the value chain, from higher yields for farmers to the promotion of exports for the international market, thus supporting the NBS (9, 29). Finally, the more direct benefits of molecular capacity to human health are evidenced by the recent COVID-19 pandemic; this has underscored the need for truly in-country molecular genetic and genomic tools for disease detection and control. The repurposing of equipment and personnel to address the crisis highlighted the transferability of molecular skills and capacity on a global scale.

Conclusion

EBP-Colombia is auspiciously timed to contribute toward Colombia's nascent transition toward a postconflict bioeconomy. By disseminating skills and tools via the EBP's network coupled with collaborative engagement from Colombia's various stakeholder groups, already it is playing a key role in the nation's capacity building and promises to accelerate the genetic characterization and exploration of its globally important eukaryotic wealth. This will advance the goals of the NBS both directly and indirectly. EBP-Colombia currently has 5 chromosome-level eukaryotic genome assemblies in progress and an estimated 54 additional draft assemblies in development. Outputs will be used to conserve as well as explore how best to utilize biological resources sustainably, replacing extractive and environmentally damaging economic practices with a bioeconomic model that can provide long-term stability and prosperity to the people of Colombia and help promote peace. If successful, the Colombian experience will provide a benchmark for other countries to follow.

Data Availability. There are no data underlying this work.

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