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Balancing Conservation and anthropogenic factors: The Integral Role of Primates in Ecosystem Regeneration

Dualisme entre conservation et facteurs anthropiques : Le rôle intégral des primates dans la régénération des écosystèmes

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Résumé

Les espèces de primates font l'objet d'une grande attention de la part des scientifiques en raison de leur extrême vulnérabilité aux pressions anthropogéniques et de leur rôle essentiel en tant que disperseurs de graines pour une grande variété de plantes tropicales, contribuant ainsi à la restauration des écosystèmes naturels. Pour survivre au milieu de diverses pressions, les primates développent des stratégies d'adaptation à la recherche de nourriture qui peuvent conduire à des conflits avec les agriculteurs locaux. La réalisation d'une revue scientifique permettra d'examiner les connaissances existantes concernant la flexibilité comportementale des primates et d'évaluer l'hypothèse selon laquelle la restauration des écosystèmes est facilitée par la dispersion des graines. Les données ont été principalement collectées via la plateforme *Publish or Perish* en saisissant des mots-clés pertinents. Cet ensemble de données comprend plus de 1517 publications, dont 557 sont pertinentes, réalisées dans 40 pays pendant un siècle, avec un accent prédominant sur l'Afrique et la région néotropicale. Naturellement, les primates réagissent aux perturbations de l'habitat en adaptant leur régime alimentaire et en modifiant l'étendue de leur aire de répartition, tout en développant des mécanismes subtils d'évitement en présence d'une surveillance humaine. Des arguments scientifiques solides soutiennent l'hypothèse selon laquelle, au cours de leurs migrations quotidiennes, les primates dispersent une multitude de graines de tailles diverses au sein des écosystèmes et des forêts, favorisant ainsi la régénération naturelle des milieux hospitaliers. Cependant, l'efficacité de la dispersion des graines est influencée par divers facteurs affectant la dynamique de régénération des écosystèmes. Ainsi, la rétention intestinale des graines, la mastication et la composition du régime alimentaire sont des facteurs critiques qui influencent à la fois la qualité et l'efficacité de la dispersion des graines par les primates, ainsi que le potentiel germinatif des graines disséminées. Les connaissances obtenues sur la flexibilité comportementale des primates et leur rôle dans la dispersion des graines sont essentiels pour orienter les futures perspectives de recherche visant à soutenir les efforts de restauration des écosystèmes.

Mots clés : Primates, flexibilité comportementale, dispersion des graines, régénération naturelle, Togo

Abstract

Primate species attract significant scientific attention due to their extreme vulnerability to anthropogenic pressures and their essential role as seed dispersers for a wide variety of tropical plants, thus contributing to the restoration of natural ecosystems. To survive amid diverse pressures, primates develop foraging adaptation strategies that can lead to conflicts with local farmers. Conducting a scientific review will enable an examination of the existing knowledge regarding the behavioral flexibility of primates and the evaluation of the hypothesis that ecosystem restoration is facilitated through seed dispersal. Data were primarily collected via the *Publish or Perish* platform through the input of relevant keywords. This dataset comprises over 1517 publications, of which 557 are pertinent, conducted across 40 countries for a century, with a predominant focus on Africa and the Neotropical region. Naturally, primates respond to habitat disturbances by adapting their diets and altering the extent of their ranges while developing subtle avoidance mechanisms in the presence of human monitoring. Robust scientific arguments support the hypothesis that during their daily migrations, primates disperse a multitude of seeds of varying sizes within ecosystems and forests, thereby promoting the natural regeneration of hospitable environments. However, the efficacy of seed dispersal is influenced by various factors affecting the regeneration dynamics of ecosystems. Thus, intestinal seed retention, mastication, and dietary composition are critical factors that influence both the quality and effectiveness of seed dispersal by primates, as well as the germinative potential of the disseminated seeds. The insights obtained regarding the behavioral flexibility of primates and their role in seed dispersal are vital for guiding future research perspectives aimed at supporting ecosystem restoration efforts.

Keywords: Primates, Behavioral flexibility, Seed dispersal, Natural regeneration, Togo

1. Introduction

The fragmentation of natural habitats is one of the predominant environmental issues of our time, leading to the degradation of these ecosystems into isolated forest patches within a landscape matrix that is profoundly anthropogenically altered (Brugiere et al. 2002; Estrada et al. 2012; Gobeil & Villard 2002; Jonsen et al. 2001; Junker et al. 2020; Mekonnen et al. 2020; Perfecto & Vandermeer 2002; Wong & Candolin 2015). Numerous wildlife species, particularly non-human primates, confront the threats posed by habitat loss and fragmentation (Dickman 2010; Estrada et al. 2017). Due to the ongoing shrinkage and degradation of their habitats, the majority of primate species are in a state of extreme vulnerability and are threatened with extinction. According to the International Union for Conservation of Nature (IUCN), over 67% of primate taxa, representing more than 348 species, are considered endangered, primarily due to the degradation of their natural habitats (IUCN 2024).

In response to habitat loss and fragmentation, many primate species take refuge in small, isolated forest fragments that are often degraded by human activities, while developing behavioral and dietary strategies for survival (Arroyo‑Rodríguez & Dias 2010;

Marsh 2003; Marsh 2013). Consequently, primates living near agricultural plots, attracted by the availability of crops, unpredictably venture into these cultivated areas, generating conflicts of use with human populations (Anderson et al. 2007; Bicca-Marques et al. 2020; Camaratta et al. 2017; Campbell-Smith et al. 2011; Hockings et al. 2015; McLennan et al. 2017). These conflicts with local communities illustrate a dynamic that is likely to intensify with the expansion of agricultural land near protected areas (Bryson-Morrison et al. 2017; Hockings & McLennan 2012; Khatun et al. 2013; Mekonnen et al. 2020). The troubling issue of crop depredation by primates, alongside its consequences, underscores the urgent need to develop strategies that promote sustainable coexistence between these animals and human communities (Hill 2002).
However, the ecological contribution of primates to ecosystem restoration through endozoochorous seed dispersal is well documented in contemporary primatology (Andresen et al. 2018; Marsh 2013; Razafindratsima et al. 2018). The ecological role of primate communities is fundamental to maintaining the balance of natural ecosystems, and their decline would constitute a long-term environmental disaster, particularly for plant communities (Aguado et al. 2022). Highlighting this ecosystem potential could provide an alternative pathway to enhance the ecological resilience of sensitive natural ecosystems in developing countries. The difficulties in managing the conflicting interactions between humans and wildlife communities, especially primates, lead to significant localized extinctions of native species, resulting in the consequent loss of the ecological potentials in which they partake (Vissoto et al. 2023). Such losses can manifest as a reduced capacity for critical ecological potentials derived from species interactions, such as seed dispersal and natural ecosystem restoration (F Folega et al. 2024; Vissoto et al. 2023).
While some scientific research on primate ecology strives to emphasize the eco-functional and ecosystemic importance of these animals in the regeneration of natural ecosystems, a systematic synthesis of the literature is essential for an expanded understanding of adaptation and resilience strategies. The aim of this literature review is to compile recent knowledge on the behavioral ecology of primates, with a focus on seed dispersal and the potential for natural ecosystem regeneration.
This article critically examines theoretical and empirical work in the ecology of the adaptive behaviour of primates in relation to their ability to influence the natural regeneration of ecosystems through seed dispersal. This oriented analysis would like to examine the current knowledge and the discovery of scientific perspectives for the mitigation of emerging ecological issues on scientific research on biodiversity conservation in the context of climate change. More specifically, this work consists of (i) analysing global trends in research from 1920 to the present on primate feeding behaviour; (ii) examining the understanding of the notion of behavioural flexibility in primates; and (iii) exploring the potential and effectiveness of natural ecosystem restoration by primates.

2. Materials and method

The specific methodological approach is divided into several key steps, ensuring a rigorous and systematic selection of relevant publications.

2.1. Preliminary Literature Search

This review of the scientific literature on food ecology, adaptive behavior of primates, and their role in the restoration of degraded habitats required two sources of data. These included data obtained through the tool Publish or Perish, which integrates the search engines of Web of Science, Google Scholar, Semantic Scholar, and Scinapse. Additional information was extracted from the main primatology journals, chosen for their high impact factor and high frequency of citations: the American Journal of Primatology, Folia Primatologica, International Journal of Primatology, and Primates (McLennan et al. 2017). On these various platforms, the preliminary search was carried out using specific keywords representing diverse research topics. These included general terms such as "primate" and "monkey," as well as more specific expressions like "dispersal" and "restoration." Combinations of keywords and their synonyms, such as "primate feeding behaviour," "feeding ecology," and "primates and seed dispersal," were also used, alternately in French and English (McLennan et al. 2017). This approach allowed for an expansion of the research scope and optimized the retrieval of relevant information while highlighting the lexical richness associated with the study of primates.
The preliminary search generated over 1517 scientific publications related to the subject. The results primarily concerned scientific articles, theses, and reports, with specific identification of the following elements: title, authors, year of publication, journal, and hyperlinks or DOI. These articles were exported from the Publish or Perish platform to Microsoft Excel for statistical processing.

2.2. Purification Process

To select relevant publications, a rigorous purification process was implemented. The preliminary analysis of the data allowed for the grouping of articles by theme based on their titles and abstracts. After grouping the data by theme, a refinement of the treatment was conducted, considering the inclusion criteria. The articles needed to contain specific information on: 1) the adaptive behavior of primates in anthropogenic habitats; 2) food ecology or behavior (McLennan et al. 2017) ; 3) seed dispersal by primates; and 4) the potential for restoring degraded landscapes. The purification process led to the exclusion of non-relevant studies, particularly those focusing specifically on areas such as social relationships, molecular biology, genetics, neurocognitive sciences, comparative anatomy, general physiology, reproduction, as well as phylogeny, taxonomy, and systematics of primates. Additionally, studies on individuals in captivity due to human influence were also deemed non-relevant.

2.3. Statistical Analysis of Publications

Following the purification by elimination of non-conforming studies, 557 relevant and adequate publications were retained for thorough statistical analysis. This analysis, conducted exclusively using Microsoft Excel, was crucial for evaluating trends, the geographic distribution of research, specific issues addressed, as well as guiding future investigations.

2.4. Final Selection for Manuscript Preparation

Following the analytical synthesis, only 95 publications were retained as the main sources for the manuscript. Selected for the diversity of their methodological approaches and their substantial contribution to the scientific debate on the topic, these publications directly informed the analysis and argumentation presented.

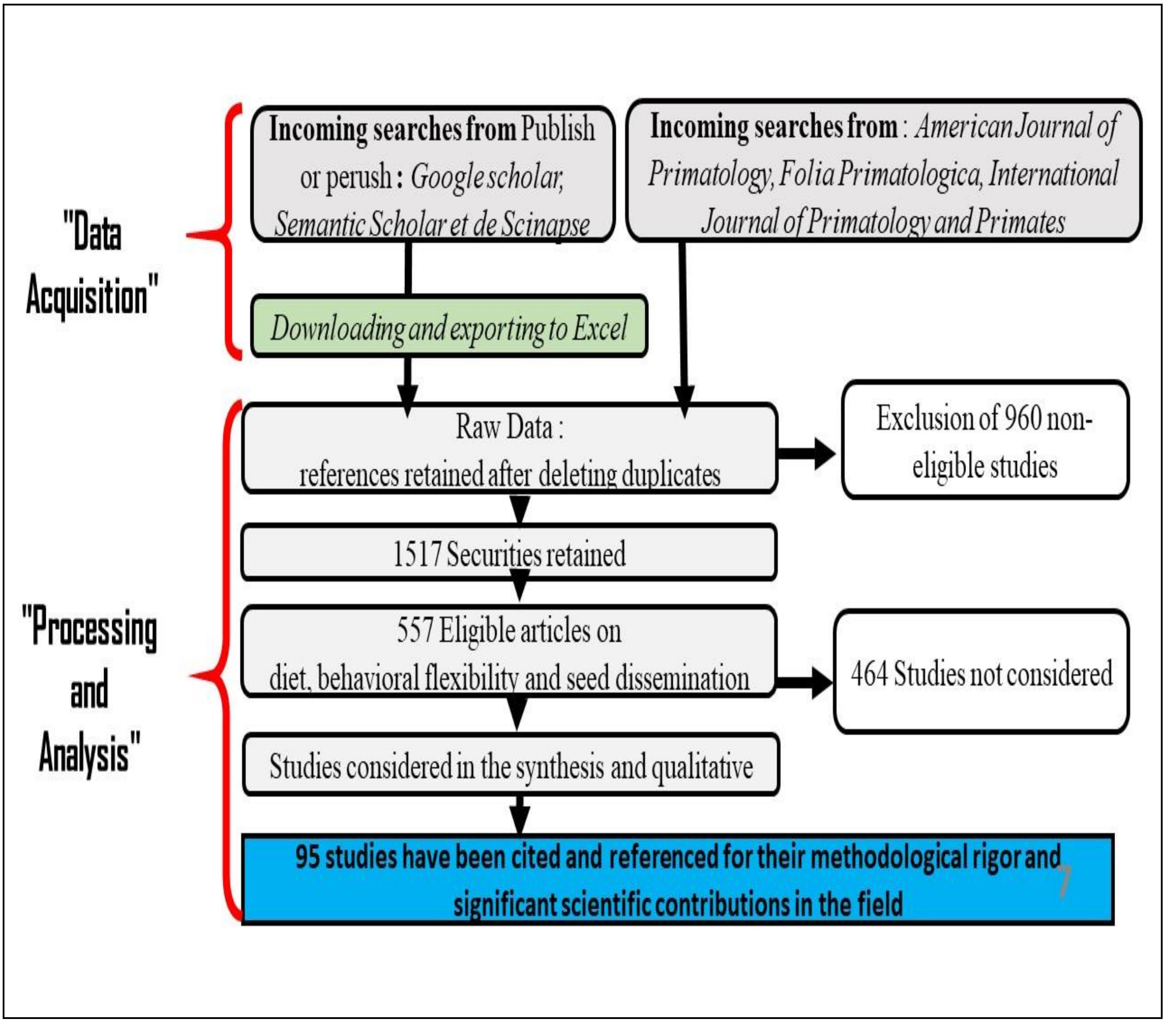

Figure 1. general methodological approach

3. Results

3.1. A Historical Perspective on Primate Feeding Behavior Research

Research on the ecology of primate feeding behavior in relation to seed dispersal in natural ecosystems and its impact on the restoration potential of these ecosystems has significantly increased since the 1970s (Humle & Hill 2016). Starting in the 1980s, ecological research in primatology experienced exponential growth, with a particular focus on the conservation of sensitive primate species. Specific themes addressing interspecific relationships between humans and primates, food ecology, and seed dispersal became the most prevalent during this period (Altmann & Muruthi 1988; Naughton - Treves 1998; Siex & Struhsaker 1999). The 2000-2010 decade was the most prolific in terms of the number of scientific works published, accounting for nearly 70% of available literature. This decade marked a turning point in primate ecology. Indeed, with the intensification of habitat degradation factors, particularly those of human origin, primatological research shifted its focus to the adaptive behavioral ecology of primates in human-modified environments (Koné et al. 2008; Szalay et al. 1987). Thus, a close link can be seen between the chronological evolution of scientific research in primatology and the exacerbation of the global biodiversity crisis and climate challenges (McLennan et al. 2017).

The significant evolution of scientific research on non-human primate behaviors in response to human-induced environmental changes highlights that this recent issue, linked to population growth, has not been a priority for researchers (Estrada et al. 2012; McLennan et al. 2017). Indeed, human population growth and the expansion of agricultural lands, which have experienced record growth rates in recent decades, are the primary modifying factors for the natural habitats of primates (Hockings et al. 2015; Humle & Hill 2016). This translation maintains the formal tone and structure typical of scientific writing.

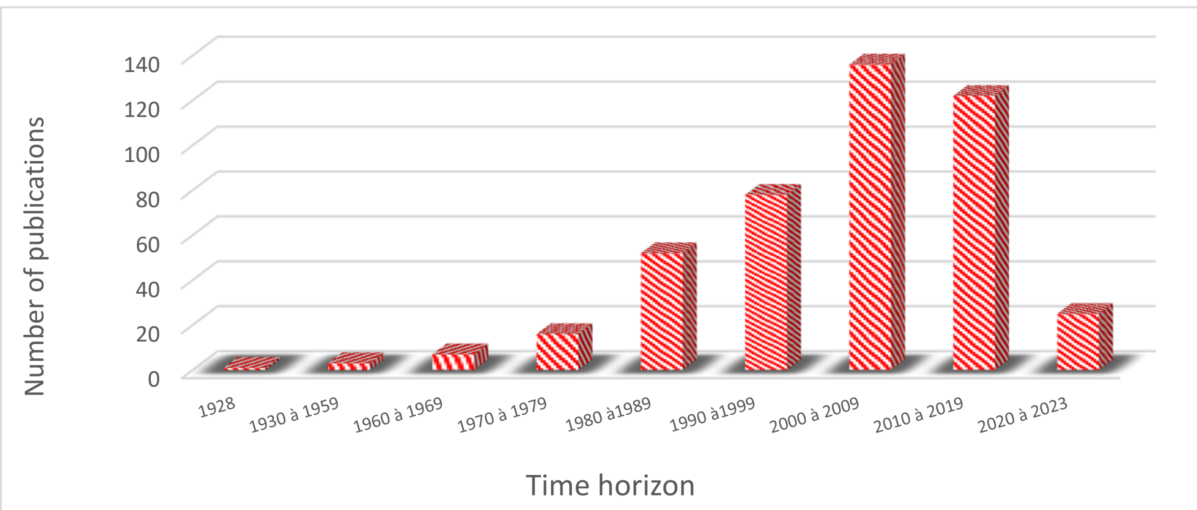

Figure 2. General Trends in Primate Behavioral Ecology Research

The selected studies are distributed across six biogeographic zones, with the majority conducted in Africa (62.31%) and in the Neotropical region (22.04%), while very few studies are undertaken in Asia (7.67%) and Madagascar (7.34%). The diversity and richness of the local biological heritage and ecosystems appear to be factors reflecting the proportional representativeness of studies by continent. Proportionally, these figures regarding the overall distribution of studies on the adaptive behavior of primates in anthropogenic habitats align with those presented by McLennan et al. (2017), highlighting the predominance of studies from continental Africa.

These studies are spread across forty countries, corresponding to the global and natural distribution of primates (Estrada et al. 2017; Estrada et al. 2012). This international geographic distribution of studies on primate behavior and the potential for ecosystem restoration highlights the most represented countries, notably Côte d'Ivoire (6.49%, or 29 studies), Benin, Brazil, and Madagascar (with 66 studies, or 5.82% each), followed by Gabon (4.25%). Moderately represented countries include Uganda and the Democratic Republic of the Congo (2.68% each), and the Republic of the Congo (2.24%). The distribution of studies by country may indicate local biological richness or the significance of scientific initiatives aimed at enhancing habitat protection against environmental pressures (Estrada et al. 2012; McLennan et al. 2017) (Figure 3).

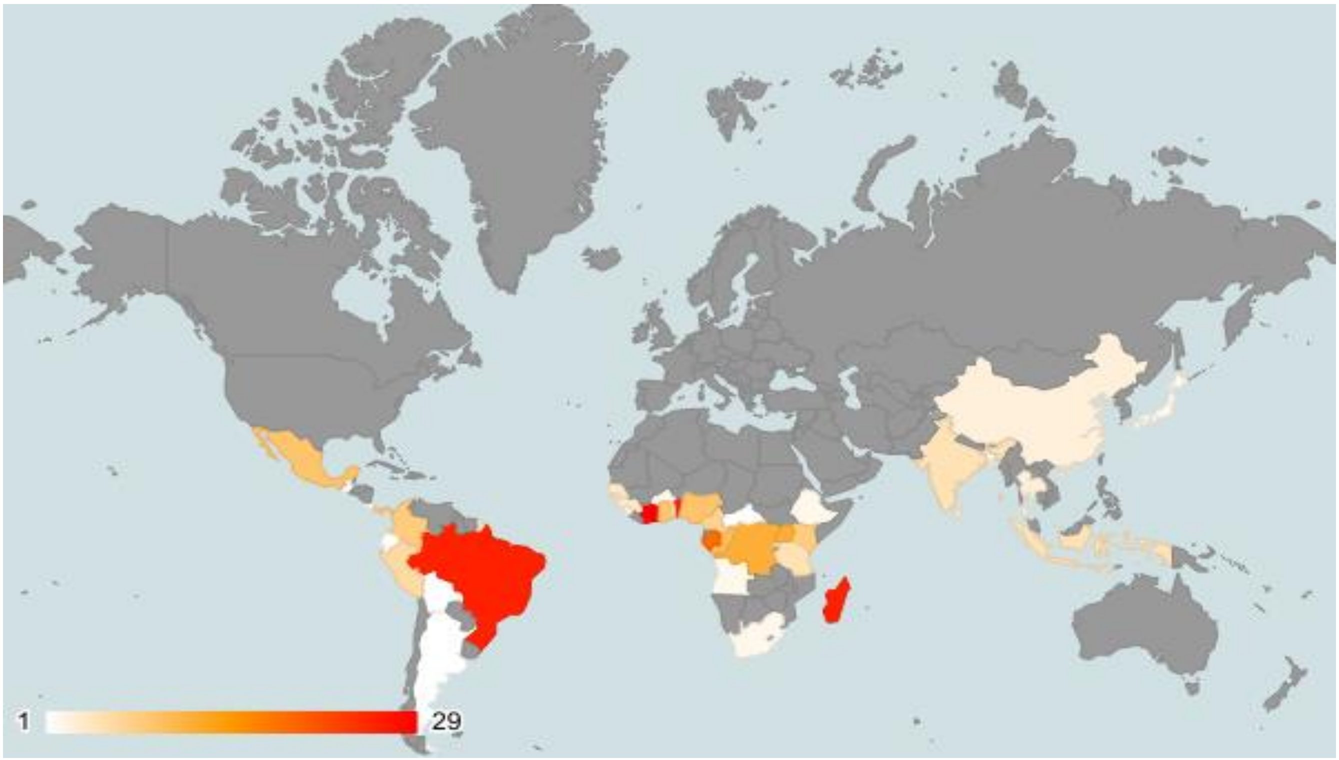

Figure 3. Global Overview of Research in Primate Behavioral Ecology

3.2. Primate Foraging Behavior

How Food Availability Influence Dietary Diversity and Primate Foraging Strategies

It is widely recognized that an organism's foraging behavior within its habitat is influenced by the abundance and availability of food resources, as well as by the presence of interspecific competitors (McLennan et al. 2017). The study of foraging behavior in animals, particularly in primates, is extensively researched on a global scale, constituting one of the foundational areas of primate behavioral ecology. Several studies have concentrated on strategies, foraging methods, time invested in food acquisition, and the tools employed (Janson 1983).

Time is a fundamental parameter in foraging ecology, particularly concerning food acquisition, whereby species can be categorized as either energy maximizers or energy minimizers (Felton et al. 2009; Kambire et al. 2021). Primates are classified as energy maximizers, which implies that they devote more time to seeking their preferred food than to resting (Felton et al. 2009; Schoener 1971). Consequently, they traverse vast areas daily in search of food and consume a diverse array of food items. This leads to a highly varied diet, largely dependent on seasonal availability, comprising primarily fruits, flowers, roots, tubers, leaves, and occasionally small arthropods (Kambire et al. 2021).

Ecological observations of foraging behavior among a group of lemurs in Madagascar reveal that they spend over 76% of their time searching for and collecting these preferred foods, with a particular emphasis on ripe fruits from approximately 34 plant species, predominantly from the Moraceae family (Chen et al. 2016; Hixon & Carpenter 1988). However, the notion of dietary preference is also strongly influenced by the seasonal availability of resources, particularly between wet and dry seasons. Brugiere et al. (2002); Chen et al. (2016) This leads to the hypothesis that spatial distribution patterns of food resources within habitats determine social dynamics and particularly the time spent foraging. This hypothesis has been confirmed in several primate species, including lemurs in Madagascar and Cercopithecinae in Gabon, whose dietary repertoires are dominated by the most prominent botanical families in their habitats, namely Moraceae, Caesalpiniaceae, and Burseraceae, respectively (Chen et al. 2016).

The influence of spatiotemporal variability in food resources is illustrated by a group of rhesus macaques whose diet consists of 90 species (primarily roots) in the autumn-winter season and expands to 193 species (predominantly fruits and young leaves) in the spring-summer season (Brugiere et al. 2002). Nevertheless, the dietary repertoire of species that varies with the seasons also exhibits significant interspecific differences. For instance, the dietary repertoire of *Euremur coronatus* may include approximately 45 plant species Liu et al. (2022); Zhang et al. (2023), while that of Cebus capucinus encompasses 105 plant species and 10 insect species (Chen et al. 2015). Furthermore, Mones de Lowe can consume over 115 plant species Wehncke et al. (2003), and Cercopithecus mitis exceeds 325 plant species in its diet (Worman & Chapman 2006).

Numerous studies on the feeding ecology of primates have highlighted significant variability in the diversity of plant organs consumed. For example, according to Zhang et al. (2023), the diet of macaques consists mainly of roots (30.9%), young leaves (28.0%), dead leaves (7.8%) and mature leaves (7.5%). In contrast, the study by Chen et al. (2015) on the Sanford brown lemur describes in greater detail the floristic composition of its virtually frugivorous diet, dominated by seven species of Moraceae, including four of the genus Ficus (*F. albidula, F. barronii, F. botryoides, F. pyrifoli*a), as well as *Pachytrophe dimepate, Streblus dimepate and Streblus madagascariensis*. This dietary specialisation could reflect a close ecological relationship between the lemur and the specific characteristics of its key habitat. According to some authors, the dietary composition of primates is not only a function of the natural availability of resources Chapman et al. (2020); Razafindratsima et al. (2018) but also of biological strategies for disease prevention. For example, Lim et al. (2021) point out that the high tannin content of Moraceae, and in particular the capacity of these iron-rich compounds, could play a role in preventing certain parasitic or deficiency diseases. Since the preferred diet of a primate species is closely tied to the availability of ecological resources, it is important to investigate how these species adapt their feeding behavior in response to the pressures caused by anthropogenic degradation of their natural habitats.

3.3. Behavioral Adaptations to Anthropogenic Environmental Changes

Certain non-human primate species are highly dependent on intact primary ecosystems, while others can adapt to secondary ecosystems and agroforestry mosaics (Worman & Chapman 2006). The flexibility of primates in response to habitat disturbances highlights the complex relationship between wildlife and an increasingly anthropogenic evolutionary environment. This flexibility is often conceived as an adaptive response for survival in changing environments (Kalbitzer & Chapman 2018). Behavioral responses encompass various biological traits of a species, including dietary modifications and socio-demographic characteristics (Schwitzer et al. 2011).

Primates are renowned for their remarkable adaptability in the face of exogenous aggression and habitat imbalance, attributable to their extraordinary cognitive abilities (Wong & Candolin 2015). In non-human primates, adaptability manifests through several mechanisms, including alterations in natural dispersal patterns toward more suitable habitats, genetic changes, and the development of behavioral flexibility. Consequently, primates can modify spatial usage of their habitat or movement patterns to cope with resource scarcity (Peres 1994). For instance, chimpanzees (*Pan troglodytes*), in response to changes in their habitats, expand their range and dietary repertoire based on resource availability (Wong & Candolin 2015). Such behavioral adjustments are common among primates living near human habitats, as a reaction to the variability in resource availability (Campera et al. 2014; Teleki & Baldwin 1979). During periods of low fruit availability, primates may turn to alternative food sources such as agricultural crops (Peres 1994). Thus, the preferential consumption of agricultural crops is regarded as a behavioral adaptation among primates residing near farmland, such as macaques (*Macaca spp*.) (McLennan et al. 2017).

This adaptation in primates often necessitates a shift in feeding schedules to minimize encounters with humans, as observed in Sumatran orangutans (*Pongo abelii*), which adjust their feeding times to late afternoon or evening when farmers are absent (Hockings & McLennan 2012). Hoest's monkeys (*Allochrocebus lhoesti*) in Uganda also synchronize their incursions into agricultural fields to avoid confrontations with humans (Campbell-Smith et al. 2011).

Despite substantial scientific evidence linking environmental disturbances to the development of adaptive behaviors in primates, the precautionary principle applies, as behavioral changes in primates are not invariably a direct result of environmental changes. Several recommendations caution against the active generalization of behavioral flexibility attributed to environmental changes, underscoring the necessity for critical evaluation (Strier 2007). Furthermore, not all primate species exhibit the same degree of adaptability. In a shared habitat undergoing modification, for example, spider monkeys (*Ateles spp*.) and woolly monkeys (*Lagothrix spp*.) living simultaneously display different vulnerabilities due to variations in reproductive characteristics and spatial dispersal capabilities (Peres & Palacios 2007).

In the context of climate change, it is crucial to understand the various responses of primates in their habitats as adaptations to evolving environmental conditions, especially since most primate populations are expected to inhabit modified forest habitats in the future (Isabirye-Basuta & Lwanga 2008). Understanding primate adaptability illuminates not only their survival strategies but also their ecological significance in maintaining the health and balance of their environments.

3.4. Seed dispersal mechanisms by primates as drivers of forest resilience

Seed dispersal is recognized as a fundamental process crucial for the structural composition and diversity of natural ecosystems. Zoochorous dispersal, where seeds are transported by animals, is particularly studied within the broader context of plant–animal interactions. It is estimated that nearly 90% of fleshy-fruited trees in tropical forests rely on animals for seed dispersal (Aguado et al. 2022; Nield et al. 2020) . Among primates, various modes of seed dispersal exist, with endozoochory being the most effective for facilitating long-distance dispersal and achieving high germination rates (Q Chen et al. 2017).

Early ecological research into plant–animal interactions highlighted the significant role of frugivorous primates in seed dispersal. This recognition continues to inspire research, providing alternative perspectives on harnessing natural ecological processes to address ecosystem degradation. Early studies focused on the quantitative aspects of seed dispersal, analyzing the volume of seeds transported. For instance, Heymann et al. (2019) demonstrated that primates could disperse an average of 392 large seeds per hectare of forest floor per week. Dispersal rates vary between species, reaching up to 1,114 seeds per day for guenons and mangabeys in Gabon (*Cercopithecus nictitans*) Mangama-Koumba et al. (2022) and more than 25,000 seeds per square kilometer per day for woolly monkeys in Colombia (Stevenson 2000). Stevenson (2000) even quantified the biomass of seeds dispersed, ranging from 1,875 to 2,948 kg/km².

Recent studies have introduced the concept of seed dispersal quantity to better explain the ecological potential of primate dispersal, noting that seeds dispersed by primates often produce more vigorous seedlings (Q Chen et al. 2017). Numerous studies have confirmed the ecosystemic importance of quantitative seed dispersal, including for lemurs Haurez (2015), gorillas, bonobos and chimpanzees, and howler monkeys (Beaune et al. 2013; Bufalo et al. 2016). Quantitative seed dispersal naturally varies between primate species depending on factors such as body size, digestive anatomy, diet, fruit size, and habitat type (Kunz & Linsenmair 2008; Poulsen et al. 2001).

Additionally, Schupp et al. (2010) demonstrated that ecological parameters, particularly the distance traveled, also influence seed dispersal patterns. In the tropical and subtropical forests of Africa and the Neotropics, primates are capable of dispersing substantial proportions of intact seeds following digestive processes, with rates reaching up to 93.6% of ingested seeds in their respective habitats (Bufalo et al. 2016).

However, supporting the hypothesis that primate-mediated zoochory contributes to natural ecosystem restoration requires solid scientific evidence, given the inherent challenges in evaluating this process (Schupp et al. 2010). The concept of Seed Dispersal Effectiveness (SDE), introduced by Gautier-Hion et al. (1985), provides a framework for assessing the ecological contributions of dispersal agents. Seed dispersal effectiveness is determined by both quantitative and qualitative components that is, the number of seeds dispersed and the probability that ingested seeds survive oral and intestinal processing, followed by successful germination across diverse microhabitats (Jordano & Schupp 2000).

Research focusing on the qualitative aspects of seed dispersal has demonstrated that primate-mediated gut passage can significantly enhance germination rates. For instance, studies on chimpanzees and the seeds of Saba senegalensis showed a 90.8% germination rate after gut passage, compared to only 51.33% for naturally fallen seeds Aguado et al. (2022). This supports the hypothesis that intestinal passage positively influences seed germination by breaking down hard seed coats and limiting the development of pathogenic organisms (Fuzessy et al. 2016). Based on this evidence, Aguado et al. (2022); Fuzessy et al. (2016) confirmed that Neotropical primates play a crucial role in shaping forest structure and dynamics by increasing germination rates by 33% and reducing germination time by 20% for endozoochoric seeds.

Several studies have also highlighted the importance of habitat type in determining the success of primate-mediated seed dispersal Tucker et al. (2018). It has been suggested that species range contraction negatively affects potential seed dispersal distances. According to Rakotomalala et al. (2017), ecological changes within a primate's home range increase the likelihood that seeds will be deposited in unsuitable habitats, thereby significantly reducing germination success.

Thus, the effectiveness of primate seed dispersal across different habitat types represents a vital ecological function, particularly important for forest succession and the restoration of degraded ecosystems. The potential for successful ecosystem regeneration through zoochorous dispersal largely depends on the biophysical suitability of the substrate in which seeds germinate (Traveset et al. 2007). Enriched substrates composed of soil mixed with fecal organic matter not only improve moisture retention but also enhance seedling survival and growth rates.

In natural ecosystems, primate movement facilitates seed dispersal across heterogeneous landscapes, increasing the likelihood that endozoochoric seeds reach suitable environments with minimal competition (Bleher & Böhning-Gaese 2001). Furthermore, gut passage has been shown to improve seed germination capacities, as evidenced once again by Saba senegalensis seeds after chimpanzee ingestion (Aguado et al. 2022).

Habitats supporting higher primate densities also exhibit greater densities of tree saplings and significantly higher species richness (Calle-Rendón et al. 2016). In Kibale National Park, Uganda, the maintenance of biological diversity has been directly attributed to the continued presence of resident primate populations (Junker et al. 2020). Thus, under natural conditions, primate-

mediated seed dispersal plays a crucial role in the regeneration of forest fragments, offering an effective and economically viable alternative for restoring degraded ecosystems (Cordeiro & Howe 2001; Koné et al. 2008).
Primates can therefore be considered flagship species for tropical forest restoration, helping to prevent extinctions and facilitate the recovery of degraded populations (Chapman et al. 2020). Additionally, forest restoration initiatives in China illustrate how efforts to conserve threatened primate populations can simultaneously promote ecosystem recovery. Overall, the multifaceted role of primates in promoting forest regeneration and biodiversity underlines their critical importance in ecological processes, highlighting the urgent need for targeted conservation efforts to protect these essential species and their habitats.

3.5. Impact of Internal and External Ecological Factors

It is well-established that primates play a crucial ecological role in seed dispersal, significantly influencing the dynamics of plant communities and the maintenance of biodiversity (Bufalo et al. 2016). However, this natural dispersal function is subject to the influence of various factors that can affect its effectiveness, and consequently, the dynamics of natural forest regeneration (Gerard 2022). Various ecological factors, such as the body size of the dispersing agent, their dietary biology, fruit characteristics, and the landscape conditions of the habitat, have been tested and deemed relevant in the literature.
Regarding the body size of dispersers, larger primates, such as gorillas and howler monkeys (*Alouatta seniculus*), are recognized for their ability to disperse a wide range of seeds of various sizes, in contrast to more modestly sized primates (Bufalo et al. 2016). The efficiency of this dispersal may also be influenced by the mechanical digestion process involved in mastication and the feeding behaviors of the animals. Indeed, the feeding behavior and dietary type of primates affect the retention time of ingested seeds, thereby impacting dispersal (Figuerola et al. 2010). A diet rich in fibers and immature fruits, coupled with intensive mastication, can reduce the retention time of seeds in the digestive (Figuerola et al. 2010; Wahaj et al. 1998).
Studies on the howler monkey, Alouatta caraya, have demonstrated that the potential for seed dispersal is positively correlated with intestinal retention time rather than the body size of the howlers. Based on this premise and the influence of feeding behavior, researchers such as Culot et al. (2010) have shown a significant correlation between seasonal fluctuations in food resources, which dictate dietary habits, and the effectiveness of seed dispersal in species such as tamarins and howler monkeys. Generally, the seed dispersal pattern exhibits a primary deposition model that is highly heterogeneous, depending on seasonal variations (Lazure & Almeida-Cortez 2006).
However, while the role of seed dispersal is essential in natural ecosystems, its effectiveness can also be affected, either positively or negatively, by secondary dispersal processes involving other taxa, particularly rodents (Y Chen et al. 2017; Dutton et al. 2014; Schurr et al. 2005). The complex interactions between primates and secondary dispersers, notably dung beetles, have implications for this effectiveness (Beaune et al. 2012). Nevertheless, secondary dispersal can also have deleterious effects, such as with rodents preying on seeds deposited in primate feces (Lazure & Almeida-Cortez 2006). Furthermore, seed predation also alters spatial distribution patterns and seedling survival (Feer et al. 2001).

4. Discussion

Primates, as key members of forest ecosystems, play a crucial role in habitat regeneration, particularly through seed dispersal. They exhibit remarkable behavioral flexibility in response to environmental changes (Q Chen et al. 2017; Koné et al. 2008). Primates demonstrate an incredible capacity to adapt to human-modified habitats through this behavioral flexibility. This adaptation encompasses dietary adjustments, such as the incorporation of human foods and crops, as well as changes in their activity patterns, movements, and social organization (Kalbitzer & Chapman 2018; McLennan et al. 2017). While some species rely on intact primary forests, others adapt to secondary forests and agroforestry mosaics (McLennan et al. 2017; Schwitzer et al. 2011). Primates living near human areas often show behavioral adaptations to mitigate conflicts (Narat 2014).
Primates exhibit varying vulnerabilities to environmental disturbances due to their reproductive characteristics and dispersal abilities (Liu et al. 2022; Lootvoet et al. 2015; Zhang et al. 2023). Species' responses to different threats are not uniform; distinct biological traits are correlated with vulnerability to specific threats such as deforestation, agriculture, and hunting (Isaac & Cowlishaw 2004). This behavioral flexibility may enable primates to adapt to rapid environmental changes, aided by their well-developed brains and long-life histories.
Through endozoochory, primates successfully disperse seeds over long distances, enhancing germination rates and the establishment of juvenile plants (Q Chen et al. 2017). This ecological function is particularly significant in anthropogenically altered ecosystems, where deforestation and intensive agriculture have diminished biodiversity and disrupted ecological processes. Research has shown that primates, especially those consuming a wide variety of fruits, are effective agents of seed dispersal, disseminating a substantial proportion of consumed seeds (72.1-93.6%) across diverse habitats, including clearings and open areas (Albert et al. 2013). Their ability to transport seeds over long distances and excrete them in conditions favorable for germination

contributes to plant diversity and ecosystem resilience. However, habitat loss, fragmentation, and agricultural expansion threaten primate populations globally, with approximately 60% of primate species at risk of extinction and 75% in decline; these threats also impact the ability of primates to play this ecological role (Isabirye-Basuta & Lwanga 2008).
Moreover, the conflicting interactions between primates and local farmers, often arising from competition for crops, are likely to worsen over time and impact the role of primates in ecosystem regeneration (Hockings & Sousa 2013; Tsakem et al. 2015). Factors such as intestinal retention time, daily travel distance, and territory size influence dispersal efficacy, further reducing primate populations and their capacity to contribute to ecosystem regeneration (Albert et al. 2013). The ability to disperse seeds into forest openings is also linked to the size of the dispersing agent (Albert et al. 2013; Bufalo et al. 2016; C Folega et al. 2024). Additionally, as mentioned, increasing conflicts with local farmers over crops may hinder primates' roles in ecosystem restoration over time (Tsakem et al. 2015).
To better leverage the role of primates in ecosystem regeneration, it is imperative to promote agricultural practices that minimize conflicts with humans (Chapman et al. 2018; Chapman & Peres 2001; Clément et al. 2024; Junker et al. 2020). Raising awareness among local communities about the importance of an integrated approach that combines research, conservation, and community engagement is essential for ensuring the survival of primates and their ecological roles.

5. Conclusion

This literature review highlights significant advancements in our understanding of primate behavioral ecology, particularly within the context of environments altered by human activity, and underscores the crucial role of endozoochoric seed dispersal by primates. Research consistently supports the notion that zoochoric dispersal, predominantly facilitated by primates, has a beneficial impact on the natural regeneration of various plant species. This finding is particularly important given that both qualitative and quantitative aspects of seed dispersal by primates serve as reliable indicators of their effectiveness in restoring degraded forests, regardless of current environmental conditions.
One of the main observations is that, without dispersal agents, a plant species may struggle to propagate beyond the founding individual, thus highlighting the critical role of animals in the plant life cycle. However, it is important to note that many empirical studies fail to integrate all relevant environmental parameters, which may lead to an oversimplified view of the dispersal process (Corlett 2017). Most studies evaluating the efficiency of seed dispersal tend to emphasize the quantity of seeds dispersed and primarily focus on the early life stages, including seed survival, germination, emergence, and short-term seedling survival. Furthermore, numerous challenges remain in estimating seed dispersal events in the field, making it difficult to fully assess the importance of this process in the regeneration of natural ecosystems. To comprehensively evaluate the impact of endozoochoric dispersal, it is essential that future research combines empirical data with spatial modeling approaches. Such integration would provide a more complete understanding of dispersal patterns and their correlations with community structure in heterogeneous landscapes (Levine & Murrell 2003; Nield et al. 2020; Schupp et al. 2010). The emergence of innovative analytical tools for tracking animal movements Nield et al. (2020) and for spatially representing seed dispersal dynamics is crucial for advancing this field of research. This multifaceted approach will not only illuminate the complexities of primate-mediated seed dispersal but will also enhance our understanding of its implications for ecosystem health and restoration efforts. Priorities include effective communication about the value of primates, increased research on interactions between primates and forests to support national restoration efforts, particularly in tropical countries (Chapman et al. 2020; Junker et al. 2020).

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