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Forestry/ Review

Techniques for the clonal forestry of Amazon tree species

Abstract – The objective of this review was to describe techniques applicable to the clonal forestry of amazon tree species, focusing on induction of epicormic sprouts, rescue, and vegetative propagation. In the Amazon, vegetative propagation and clonal forestry present a significant potential for ecological restoration and commercial applications. Studies are being carried out on the application of clonal forestry to Amazon tree species, aiming forestry production and the restoration of degraded or altered ecosystems. However, the available protocols are still unclear as to the techniques, propagules, and propagation processes to be used. Despite the success of techniques such as cuttings and micropropagation in species as *Hevea brasiliensis* and *Theobroma cacao*, there are still challenges, such as limited genetic material and high costs. To address these and other challenges, it is crucial to adopt integrated approaches, such as collaborative research networks and data platforms, inspired by international practices. Here, bibliographic data on over 100 species, knowledge gaps, and future perspectives are presented. Future advancements should focus on optimizing techniques, expanding genetic research, and fostering collaboration among stakeholders.

Index terms: cuttings technique, grafting, layering technique, mini-cuttings technique, vegetative propagation, vegetative rescue.

Técnicas para a silvicultura clonal de espécies arbóreas da Amazônia

Resumo – O objetivo desta revisão foi descrever técnicas aplicáveis à silvicultura clonal de espécies arbóreas da Amazônia, com foco em indução de brotações epicórmicas, resgate e propagação vegetativa. Na Amazônia, a propagação vegetativa e a silvicultura clonal apresentam grande potencial para restauração ecológica e aplicações comerciais. Estão sendo realizados estudos sobre a aplicação da silvicultura clonal em espécies arbóreas nativas da Amazônia, tendo como objetivo a produção florestal e a restauração de ecossistemas degradados ou alterados. No entanto, os protocolos disponíveis não são claros sobre as técnicas, os propágulos e os processos de propagação que devem ser utilizados. Apesar do sucesso de técnicas como estacas e micropropagação em espécies como *Hevea brasiliensis* e *Theobroma cacao*, ainda há desafios como material genético limitado e altos custos. Para superar esses e outros desafios, é crucial adotar abordagens integradas, como redes de pesquisa colaborativa e plataformas de dados, inspiradas em práticas internacionais. Aqui, são apresentados dados bibliográficos de mais de 100 espécies, lacunas de conhecimento e perspectivas futuras. Futuros avanços devem focar na otimização de técnicas, na expansão da pesquisa genética e na colaboração entre as partes interessadas.

Termos para indexação: estaquia, enxertia, mergulhia, miniestaquia, propagação vegetativa, resgate vegetativo.

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1. Introduction

Clonal forestry can be effectively applied to native species, not only for the production of wood and non-timber products, but also for the restoration and rehabilitation of degraded forests, while maintaining genetic diversity, in addition to further diversifying the uses of forest resources and promoting a more comprehensive environmental recovery (Stuepp et al., 2018). However, in the Amazon region, the clonal forestry of Amazon tree species does not go beyond the initial experimental stages, whereas that of the genus *Eucalyptus* is expanding (Almeida & Vieira, 2022).

The incipient knowledge about the potential use and management of Amazon tree species has limited the application of rescue and propagation techniques in clonal forestry. Combined with the lack of advancement of knowledge on native species compared with exotic ones, one-off studies (without interaction with other studies) or discontinued studies have raised the need for the discussion about the potential of those species and how researches have been carried out so far (Xavier et al., 2021).

For a successful application of clonal forestry using Amazon tree species, it is important to understand the preceding steps, such as the establishment of basic criteria and vegetative rescue. Studies on vegetative rescue have highlighted the importance of juvenile propagules for vegetative propagation, as well as the efficiency of propagules from basal epicormic sprouts (Sales et al., 2024). In this line, several authors have reported promising results while using juvenile propagules, either with young plants or basal sprouts (Wendling et al., 2014a, 2014b).

Vegetative propagation is a particularly valuable technique for the production of plants from species that face challenges with sexual reproduction and for the restoration of degraded areas, representing an effective method for the fixation of selected genotypes, facilitating the establishment of uniform and productive clonal plantations while enhancing the quality of wood and other derived products (Xavier et al., 2021). However, despite its advantages, clonal propagation can lead to a reduction in genetic diversity within plant populations.

Since the reduction in genetic variability may compromise the adaptability and resilience of species in the face of environmental changes and pathogenic pressures, it is essential to implement strategies that integrate vegetative propagation with measures aimed at conserving genetic diversity. Such strategies may include maintaining germplasm banks, performing controlled crosses to introduce genetic variability, and employing management practices that promote genetic diversity over time. In a balanced approach, both clonal production and the conservation of genetic diversity are considered critical to ensure the long-term sustainability and health of plant species and the ecosystems they support (Stuepp et al., 2018).

In the literature, several methodologies have been used for the rescue and vegetative propagation of Amazon tree species for productive and environmental purposes. However, there is still no consensus regarding the types and goals of the applied techniques, showing an evident gap in knowledge. This and the great potential of these tree species in clonal forestry motivate an understanding of the techniques applicable to each purpose through the interaction between published studies.

This review presents bibliographic data from over 100 species, knowledge gaps to be filled, and future perspectives. For this, it begins with a comprehensive analysis of the techniques for the induction of juvenile sprouts and vegetative rescue, exploring how these methods are being used for the rescue and propagation of Amazon tree species. Subsequently, primary methodologies for vegetative propagation were examined, including seed propagation, seedling cultivation, and cloning methods such as cuttings, mini-cuttings, grafting, and micropropagation, highlighting their specific applications and limitations for different species. Finally, the future prospects for clonal forestry in the Amazon were discussed, addressing the challenges encountered and the opportunities to advance in its practical implementation.

2. Amazon tree species

This review presents bibliographic information on over 100 tree species found in the Amazon Rainforest, with different potential for clonal forestry (Table 1). These species were selected due to their significance to the Brazilian forestry sector, the established knowledge about them, and the available literature.

The used references were selected through a systematic review of the literature in order to identify studies pertinent to clonal forestry techniques applied

Table 1. Scientific and common name in Brazil of the native tree species of the Amazon region cited in this review, in alphabetical order.

Scientific name (common name)	
Acca sellowiana (O. Berg) Burret (*goiabeira-serrana*)	*Inga alba* (Sw.) Willd. (*ingá-vermelho*)
Amburana acreana (Ducke) A.C.Sm. (*cerejeira*)	*Inga marginata* Willd. (*ingá-feijão*)
Anacardium occidentale L. (*cajueiro-anão*)	*Inga subsericantha* Ducke (*ingá-xixica*)
Anadenanthera colubrina var. cebil (Vell.) Brenan (*angico-branco*)	*Inga vera* Wild. (*ingá-do-brejo*)
Aniba rosaeodora Ducke (*pau-rosa*)	*Lecythis idatimon* Aubl. (*matamatá-vermelho*)
Annona glabra L. (araticum-do-rio)	*Lecythis pisonis* Cambess (*sapucaia*)
Annona montana Macfad (*araticum-do-mato*)	*Maclura tinctoria* (L.) D.Don ex Steud. (*taúba*)
Annona squamosa L. (*pinheira*)	*Macrolobium* sp. (*araparizinho*)
Apuleia leiocarpa J.F.Macbr (*garapa*)	*Magnolia ovata* Spreng (*pinha-do-brejo*)
Aspidosperma polyneuron Müll.Arg. (*peroba-rosa*)	*Manilkara huberi* Standl. (*maçaranduba*)
Aspidosperma ramiflorum Müll.Arg. (*guatambu-amarelo*)	*Maytenus evonymoides* Reissek (*tiriveiro*)
Bertholletia excelsa Bonpl. (*castanha-do-pará*)	*Metrodorea flavida* K.Krause (*café-bravo*)
Bixa orellana L. (urucum)	*Miconia albicans* (Sw.) Steud. (*canela-de-velho*)
Cabralea canjerana (Vell.) Mart. (*canjarana*)	*Miconia ibaguensis* Triana (*miconia*)
Caesalpinia pyramidalis Tul. (*catingueira*)	*Mimosa caesalpiniifolia* Benth. (*sabiá*)
Calophyllum brasiliense Cambess (*guanandi*)	*Moringa oleifera* Lam. (*moringa*)
Calycophyllum spruceanum (Benth) Hook.f. ex K.Schum. (*pau-mulato*)	*Myracrodruon urundeuva* Allemão (*aroeirinha*)
Carapa guianensis Aubl. (*andiroba*)	*Myrciaria dubia* (Kunth) McVaugh (*camu-camu*)
Cariniana estrellensis (Raddi) Kuntze (*jequitibá-branco*)	*Peltophorum dubium* (Spreng.) Taub. (*canafístula*)
Casearia sylvestris Sw. (*guaçatonga*)	*Piper arboreum* Aubl. (*fruto-de-morcego*)
Cecropia pachystachya Trécul (*embaúba*)	*Plathymenia foliolosa* Benth. (*vinhático*)
Cecropia spp. (*embaúba*)	*Plathymenia reticulata* Benth. (*vinhático*)
Caryocar cuneatum Wittm (*pequi*)	*Pouteria* sp. (*abiú*)
Cedrela fissilis Vell. (*cedro-rosa*)	*Psidium cattleyanum* Sabine (*araçazeiro*)
Cedrela odorata L. (*cedro*)	*Psidium chinensis* viz. (*araçá*)
Celtis sp. (*juazeiro-de-bode*)	*Psidium cujavillus* Burm.f. (*araçá*)
Copaifera langsdorffii Desf. (*copaíba*)	*Psidium friedrichsthalianum* Nied. (*araçá*)
Cordia alliodora (Ruiz & Pav.) Oken (*louro-freijó*)	*Psidium guajava* L. (*goiabeira*)
Cordia trichotoma (Vell.) Steud. (*louro-pardo*)	*Psidium guineense* Sw. (*araçá-do-campo*)
Couepia edulis (Prance) Prance (*castanha-de-cutia*)	*Redhia gardneriana* Miers ex Planch e Triana (*bacuripari*)
Croton urucurana Baill. (*urucurana*)	*Rinorea guianensis* Aubl. (*acariquarana*)
Cupania oblongifolia Mart. (*camboatá*)	*Rollinia emarginata* (Schltdl.) (*araticum-mirim*)
Dendropanax cuneatus Decne. & Planch. (*maria-mole*)	*Rollinia mucosa* (Jacq.) Baill. (*biribá*)
Didymopanax morototoni Decne. & Planch. (*morototó*)	*Rollinia rugulosa* Schltdl. (*araticum-de-porco*)
Dipteryx alata Vogel (*barú*)	*Rollinia* sp. (*araticum-de-terra-fria*)
Erythrina velutina Willd. (*bucaré*)	*Sagotia racemosa* Baill. (*aratacíú*)
Eschweilera longipes Miers (*mori*)	*Salix humboldtiana* Willd. (*salgueiro*)
Euplassa inaequalis Engl. (*fruto-de-morcego*)	*Schizolobium parahyba* var. amazonicum (Ducke) Barneby (*paricá*)
Ficus adhatodifolia Schott ex Spreng. (*gameleira*)	*Sclerolobium paniculatum* Vogel (*tachi-branco*)
Ficus citrifolia Mill. (*figueira*)	*Sebastiania schottiana* Müll.Arg. (*sarandi*)
Genipa americana L. (*jenipapeiro*)	*Siparuna guianensis* Aubl. (*negramina*)
Guazuma crinita Mart. (*bolaina*)	*Spondias mombin* L. (*cajazeira*)
Guazuma ulmifolia Lam. (*embira*)	*Spondias purpurea* L. (*ciriguela*)
Hancornia speciosa Gomes (*mangabeira*)	*Spondias* sp. (*cajarana*)
Handroanthus chrysotrichus (Mart. ex DC.) Mattos (*ipê-amarelo*)	*Spondias tuberosa* Arruda (*umbuzeiro*)
Handroanthus heptaphyllus (Vell.) Mattos (*ipê-roxo*)	*Stryphnodendron polyphyllum* Mart. (*barbatimão*)
Handroanthus impetiginosus (Mart. ex DC.) Mattos (*ipê-rosa*)	*Swietenia macrophylla* King in Hook. (*mogno*)
Handroanthus roseo-albus (Ridl.) Mattos (*ipê-branco*)	*Tapirira guianensis* Aubl. (*tapiriri*)
Hevea brasiliensis (Willd. ex A.Juss.) Müll.Arg. (*seringueira*)	*Theobroma cacao* L. (*cacaueiro*)
Himatanthus sucuuba (Spruce) Woodson (*sucuuba*)	*Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum. (*cupuaçu*)
Hymenaea courbaril L. (*jatobá*)	

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to Amazon tree species. The criteria used for their inclusion in this review were based on the relevance of the species to clonal forestry, the type of research, and the applicability of the described techniques, aiming to ensure a robust representation of up-to-date knowledge and practices. With this information, the current state of clonal forestry implementation was addressed, while evaluating which native tree species show promise for future development and the potential directions for the field.

Considering their diverse range of families, genera, and purposes (wood, resins, leaves, fruits, flowers, seeds, and environmental applications), the reviewed species can be used as a foundational reference for further research on other native species that could be valuable for clonal forestry.

3. Induction of juvenile sprouts in Amazon tree species

The induction of epicormic sprouts, which are juvenile sprouts originating from latent axillary buds, is used to rescue juvenile characteristics in adult plants (Almeida et al., 2014). For most part, the purpose of this technique is to replace the crown through grafting or to obtain juvenile propagules to be used in association with other vegetative propagation techniques (Kratz et al., 2016) without phytoregulators (Wendling et al., 2014b).

Among the other vegetative propagation techniques, coppicing, girdling, and drastic pruning have been used to rejuvenate and reinvigorate native tree species by evaluating the effectiveness and conservation of the mother tree (Xavier et al., 2021).

In coppicing, trees are cut at different heights, leading to a strong vegetative response and to the regeneration of new shoots from the base. When carried out close to the stem base, this method is more efficient at stimulating epicormic sprouts due to the greater juvenility of the buds in this part of the plant (Wendling et al., 2014b). For these reasons, coppicing has been recommended to induce sprouting in native tree species, aiming the rejuvenation and/or reinvigoration of adult plants (Sampaio et al., 2007; Kratz et al., 2016), especially for productive purposes and forest restoration in degraded areas. This technique has allowed of reaching high emission rates of epicormic sprouts in *Hevea brasiliensis* (Willd. ex A. Juss.) Müll.Arg., *Aniba rosaeodora* Ducke, and *Calophyllum brasiliense* Cambess. (Kratz et al., 2016), also being efficient in other species, such as *Cordia alliodora* (Ruiz & Pav.) Oken, *Cedrela fissilis* Vell., *Cecropia pachystachia* Trecul, *Calycophyllum spruceanum* (Benth) K. Schum., *Cordia trichotoma* (Vellozo) Arrabida ex Steudel, *Inga marginata* Willd., *Peltophorum dubium* (Sprengel) Taub., and *Schizolobium parahyba* var. *amazonicum* (Ducke) Barneby (Table 1). However, in some studies, stump vigor and productivity have not yet been evaluated, requiring further research (Ohashi et al., 2004; Krainovic et al., 2017).

Total or partial girdling is a technique that can be applied at different heights, stimulating sprouting below the made incision. It is an option that causes less damage to the mother tree than coppicing, also being an alternative for trees with advanced age (physiological, ontogenetic, and chronological), low vigor and/or poor phytosanitary conditions, or for species that have legal restrictions, such as *Bertholletia excelsa* Bonpl., *Hevea* spp., and *Swietenia macrophylla* King in Hook (Wendling et al., 2014a).

Total girdling is a technique for rescuing trees with a high genetic value, but can result in a lower sprout productivity compared with coppicing (Kratz et al., 2016). Although it is considered promising for the vegetative rescue of species or mother trees in field conditions, this type of management can be difficult to carry out without damaging mother trees, whose chances of healing and survival can be increased by a trained operator (Almeida et al., 2014).

Partial girdling is less used than total girdling due to a lack of specificity in research using this technique (Stuepp et al., 2018). Although less efficient in inducing epicormic sprouts in native tree species than coppicing and total girdling, in this order (Kratz et al., 2016), partial girdling is an important alternative for preserving unique or protected genetic materials. The application of total and partial girdling, for example, has shown efficiency in inducing epicormic sprouts in some Amazon tree species (Table 2).

Other techniques for inducing epicormic sprouts in native trees include pruning of canopy branches, sprouting of detached branches kept in a greenhouse, stem span, and fire use at the base of the trees.

Pruning of canopy branches is a method in which all or part of the tree's canopy is removed, being pruned back to

Table 2. Techniques of coppicing, total and partial girdling, pruning of canopy branches, sprouting of detached branches kept in a greenhouse, stem span, and fire use applied for the induction of epicormic sprouts in Amazon tree species.

Species	Purpose(1)	Period	Age(2)	H(3)	Sprout(4)	Length(5)	Ø(6)	Eff.(7)	Reference
Coppicing									
Aniba rosaeodora	Cuttings	November	Adult(5)	-	-	150.0	-	-	Sampaio et al. (1989)
Aniba rosaeodora	RM(8)	-	22	15, 30, 45	<5	3.4	3.1	100.0	Ohashi et al. (2004)
Aniba rosaeodora	RM	April	19	100	<7	430.0	4.9	60.0	Sampaio et al. (2005)
Aniba rosaeodora	RM	-	36	-	<27	<140.0	<7.0	-	Sampaio et al. (2007)
Aniba rosaeodora	RM	June	10, 12, 17	50	9	<85.0	<0.5	25	Krainovic et al. (2017)
Cordia alliodora	RM	-	5	50	<16	-	-	-	Hummel (2000)
Calophyllum brasiliense	Cuttings	October	14	30	-	-	-	100.0	Kratz et al. (2016)
Cedrela fissilis	RM	-	2 to 15	-	-	-	<20.0	56.0	Kammesheidt (1998)
Cecropia pachystachia	RM	-	2 to 15	-	-	-	<25.0	38.0	Kammesheidt (1998)
Calycophyllum spruceanum	RM	October	-	30	<12	<200.0	-	-	Boivin-Chabot et al. (2004)
Cordia trichotoma	RM	-	2 to 15	-	-	-	<15.0	68.0	Kammesheidt (1998)
Inga marginata	RM	-	2 to 15	-	-	-	<15.0	25.0	Kammesheidt (1998)
Peltophorum dubium	RM	-	2 to 15	-	-	-	<25.0	71.0	Kammesheidt (1998)
Schizolobium parahyba var. *amazonicum*	RM	March	6	-	-	50.0	-	52.2	Pereira et al. (2013)
Total girdling									
Calophyllum brasiliense	Cuttings	Spring	14	30	-	-	-	90.0	Kratz et al. (2016)
Theobroma grandiflorum	Invigoration	-	15	25	<7	-	-	-	Almeida et al. (2014)
Partial girdling									
Calophyllum brasiliense	Cuttings	Spring	14	30	-	-	-	30.0	Kratz et al. (2016)
Pruning of canopy branches									
Annona squamosa	Invigoration	June	3	20	-	<94.5	-	-	Dias et al. (2003)
Annona squamosa	Invigoration	February	5	5 to 30	<5	<22.5	-	-	Dias et al. (2004)
Annona squamosa	Invigoration	May	5	25	-	<25.5	<6.5	-	Santos et al. (2014)
Heve brasiliensis	Grafting	-	-	-	-	-	-	-	Pereira et al. (2019)
Theobroma cacao	Mini-cuttings	March	0.6		<5	-	-	-	Pereira (2018)
Theobroma grandiflorum	Invigoration	-	15	-	<16	-	-	-	Almeida et al. (2014)
Sprouting of detached branches kept in a greenhouse									
Bertholletia excelsa	Cuttings	-	23	40	<5	7.9	0.4	0.0	Conceição et al. (2020)
Lecythis pisonis	Cuttings	October	Adult(9)	60	<7	<4	-	0.0	Bernardes et al. (2020)
Myrciaria dubia	Cuttings	-	34	40	<19	-	-	-	Lima et al. (2020)
Myrciaria dubia	Cuttings	-	-	20	<29	-	-	-	Lima et al. (2020)
Stem span									
Theobroma cacao	Mini-cuttings	December	0.6	-	<36	-	-	-	Pereira (2018)
Use of fire									
Cordia alliodora	RM	August	-	<30 and >30	-	-	-	<100.0	Triana (2019)
Cecropia spp.	RM	August	-	-	-	-	-	15.0	Kauffman (1991)
Eschweilera longipes	RM	August	-	-	-	-	-	67.0	Kauffman (1991)
Iinga alba	RM	August	-	-	-	-	-	56.0	Kauffman (1991)
Inga subsericantha	RM	August	-	-	-	-	-	63.0	Kauffman (1991)
Lecythis idatimon	RM	August	-	-	-	-	-	29.0	Kauffman (1991)
Metrodorea flavida	RM	August	-	-	-	-	-	33.0	Kauffman (1991)
Manilkara huberi	RM	August	-	-	-	-	-	21.0	Kauffman (1991)
Pouteria sp.	RM	August	-	-	-	-	-	21.0	Kauffman (1991)
Rinorea guianensis	RM	August	-	-	-	-	-	63.0	Kauffman (1991)
Sagotia racemosa	RM	August	-	-	-	-	-	32.0	Kauffman (1991)

(1)Reason why the technique was applied. (2)Estimated age of the mother tree in years. (3)Height at which the technique was applied. (4)Number of shoots per stump, stem, or branch. (5)Sprout length. (6)Sprout diameter (cm). (7)Percentage of plants sprout emission after the application of the technique. (8)RM, regrowth management. (9)Adult mother trees. -, No information available.

its main branches to re-form the canopy. The technique is used to reinvigorate species, such as *Annona squamosa* L. and *Theobroma grandiflorum* (Willd. ex Spreng.) Schum. (Almeida et al., 2014; Santos et al., 2014), or to provide propagules in species as *H. brasiliensis* and *T. cacao* (Pereira et al., 2019), especially for micropropagation, grafting, or mini-cuttings.

The technique of sprouting of detached branches kept in a greenhouse is used to induce epicormic sprouts, being consolidated for *B. excelsa* and *Myrciaria dubia* (HBK) Mc Vaugh for the propagation of cuttings (Conceição et al., 2020; Lima et al., 2020). These sprouts are also stimulated by the stem span technique, but by being bent towards the ground without being broken, which has been reported for *T. cacao* (Pereira, 2018).

The use of fire is a method based on the degradation of auxins, used to induce basal sprouts in trees by increasing temperature, promoting the emergence of new sprouts below the part damaged by the fire (Xavier et al., 2021). These authors recommend this technique for the vegetative rescue of native tree species, especially when other more invasive methods are not possible. Promising results have been obtained for native tree species, including *C. alliodora*, *Eschweilera longipes* (Goit) Miers, *Inga alba* (Sw.) Willd., and *Rinorea guianensis* Aubi. (Table 2).

Despite the aforementioned studies, the vegetative rescue techniques through the induction of epicormic sprouts in Amazon tree species still remain relatively underexplored. Although species such as *A. rosaeodora*, *C. brasiliense*, and *C. alliodora* show a promising potential, there is a notable paucity of detailed information regarding their ability to produce epicormic sprouts and their vegetative vigor for the purposes of rejuvenating or rescuing senescent trees. Almeida et al. (2014) and Wendling et al. (2014b) added that, while techniques as coppicing and girdling have shown effectiveness in certain species, the variability in the response of different species and the overall success of these methods are not well-documented. Moreover, the effectiveness of these techniques can be significantly influenced by factors such as tree age, physiological condition, and environmental conditions, as discussed by Ohashi et al. (2004) and Kratz et al. (2016). Therefore, the limitations in current research include a lack of comprehensive longitudinal studies and few targeted investigations to evaluate the specific responses of the cited Amazon tree species. Addressing these gaps could provide a more robust understanding of the viability and optimization of vegetative rescue techniques in tropical forest restoration and conservation efforts.

4. Vegetative rescue in Amazon tree species

When studying native tree species, it is important to differentiate between vegetative rescue and propagation, whose respective aims are to obtain at least one individual genetically identical to the mother tree and to multiply on an experimental or a commercial scale (Stuepp et al., 2018). For these techniques, juvenile propagules, most easily obtained from young plants and basal epicormic shoots, are generally used, but more mature propagules may be needed when adventitious shoots of the species are not obtainable or when the tree is legally protected, a choice that may also depend on the purpose of obtaining the propagules (Bernardes et al., 2020). Understanding and intensifying vegetative rescue and propagation is necessary to advance in the clonal forestry of Amazon tree species, which includes standardizing methods and selecting appropriate materials.

In the case of rescue, canopy sprouts or basal epicormic shoots can be used, each method with its advantages and disadvantages, defined according to the species and the desired results (Stuepp et al., 2018). Xavier et al. (2021) highlighted that studies on vegetative rescue provide important information, such as ontogenetic age effects, which vary according to the applied technique.

4.1 Vegetative rescue by canopy sprouts

In clonal forestry, the vegetative rescue through sprouts on parts of tree branches and twigs is carried out by grafting, cuttings, rooting, and layering, with the aim of obtaining flowers, fruits, and seeds for productive purposes (Deshlehra et al., 2019). Mature propagules are more able to maintain maturity characteristics (Lima et al., 2020), whereas canopy sprouts are useful for genetic conservation, both in situ and ex situ, in programs for breeding and for the restoration of degraded ecosystems through genetic rescue, whose objective is to preserve alleles to increase effective population size, favor heterozygosity, and reduce population inbreeding (Xavier et al., 2021).

In studies with native tree species, crown shoots with the cuttings technique was one of the first used methodologies, making shoots readily available, without causing serious damage to the mother tree, despite inhibiting rhizogenesis (Stuepp et al., 2018). In experiments with crown shoots, the capacity for rhizogenesis has been shown to be influenced by species, tree ontogeny, collection methodologies, and climatic conditions (Wendling et al., 2014a).

Although rooting percentages are generally low, the vegetative rescue of adult plants is viable, especially since the propagation of the rooted materials can be continued with other more efficient methods, such as the grafting, cuttings, or mini-cuttings techniques. However, the cuttings technique is not recommended for multiplying the crown genetic material of species that are difficult to root according to the principle of propagule maturation (Wendling et al., 2014b).

4.2 Vegetative rescue by basal epicormic shoots

Although it is possible to rescue trees using techniques such as grafting, layering, or cuttings from crown shoots, the rooting performance of the obtained propagules and the physiological quality of the resulting plants can be enhanced by rejuvenation techniques, such as the induction of sprouting of basal epicormic shoots (Wendling et al., 2014a).

Basal epicormic shoots, due to their juvenile characteristics, often exhibit a higher rooting potential and vegetative vigor (Conceição et al., 2020). The first studies on the rooting of these shoots in native species were carried out using *H. brasiliensis* (Muzik & Cruzado, 1956), but other species also performed well, including *A. rosaeodora* and *C. brasiliense* (Sampaio et al., 1989; Ciriello & Mori, 2015). However, although there is evidence of the effectiveness of this technique, available information is still limited (Wendling et al., 2014b).

4.3 Vegetative rescue using canopy sprouts and basal epicormic shoots

Even though crown shoot rooting has a low efficiency (Table 3), which does not reach 1% in some cases (Schwengber et al., 2000; Scaloppi Junior, 2007), when rooting does occur, it still can facilitate subsequent clonal propagation. This allows of the use of more effective techniques such as cuttings, mini-cuttings, and grafting, which can be combined with clonal hedges and mini-clonal hedges to enhance propagation efficiency and expand the clonal population.

Although the cuttings technique can be used for vegetative rescue in specific scenarios, the available data suggest that basal shoots, which are typically more juvenile, may offer a more effective alternative for a greater rooting success. Ciriello & Mori (2015) found that, despite the capability of some species, such as *C. brasiliense*, of forming adventitious roots from crown propagules, the overall rooting success and root vigor remain suboptimal compared with those of juvenile propagules. Santos et al. (2011) also observed a particularly low rooting efficiency in mature species as *I. marginata* and *Inga vera* Willd, which presented a minimal adventitious rooting capability. Therefore, cuttings are generally not recommended for rooting crown propagules in tree species due to their degree of maturity (Wendling et al., 2014b). A preferable method for vegetative rescue may be cuttings derived from basal shoots (Xavier et al., 2021).

Grafting is widely used in the clonal forestry of native tree species to provide more adaptable rootstocks and genetically superior and highly productive grafts (Carvalho & Nascimento, 2016), as well as to rejuvenate adult propagules via serial grafting onto juvenile rootstocks (Xavier et al., 2021). With the technique, native tree species are breed, forming indoor or outdoor clonal orchards for controlled crossings and improved seed production, as reported for *Hymenaea courbaril* L., *Handroanthus heptaphyllus* (Vell.) Mattos, and *S. macrophylla* (Mendes, 2019).

While grafting is generally effective in producing flowers, fruits, and seeds, and in perpetuating desirable traits from the mother tree, several limitations have been identified in the literature. Mendes (2019), for example, noted that the efficiency of grafting can be significantly reduced when performed in series due to cumulative physiological stress and a decreased compatibility between rootstocks and scions. Additionally, difficulties such as the high cost of maintaining clonal orchards and the need for precise environmental control have constrained the widespread application of grafting techniques (Table 4). Perspectives on overcoming these challenges include advancements in the grafting technology and an improved selection of compatible rootstock-scion combinations, which could enhance both the efficiency and scalability in clonal propagation. In addition to the compatibility

Table 3. Vegetative rescue using crown and basal sprouts by the cuttings technique in Amazon tree species.

Species	Growth regulator[1]	Survival (%)	Efficiency[2]	Reference
		Crown sprout		
Annona montana	1,000, 3,000, 5,000, and 7,000 mg L^{-1} IBA	<95	<48.0	Scaloppi Junior & Martins (2003)
Annona glabra	1,000, 3,000, 5,000, and 7,000 mg L^{-1} IBA	<68	<94.0	Scaloppi Junior & Martins (2003)
Calophyllum brasiliense	1,000, 2,000, and 4,000 mg L^{-1} IBA	-	0.0	Rios & Ribeiro (2014)
Calophyllum brasiliense	100, 1,000, 5,000, and 10,000 mg L^{-1} IBA	100	<25	Ciriello & Mori (2015)
Casearia sylvestris	100, 200, and 300 mg kg^{-1} IBA	-	0.5	Santos et al. (2011)
Copaifera langsdorffii	1,000, 2,000, and 4,000 mg L^{-1} IBA	-	0.0	Rios & Ribeiro (2014)
Couepia edulis	3,000 and 6,000 mg L^{-1} IBA	-	<15.0	Leandro & Yuyama (2008)
Croton urucurana	100, 200, and 300 mg kg^{-1} IBA	-	23.0	Santos et al. (2011)
Cupania oblongifolia	3,000 and 6,000 mg L^{-1} IBA	4	3.3	Parajara (2015)
Dendropanax cuneatus	100, 200, and 300 mg kg^{-1} IBA	-	0.0	Santos et al. (2011)
Euplassa inaequalis	2,000, 4,000, and 8,000 mg L^{-1} IBA	<83	5.4	Oliveira & Ribeiro (2013)
Ficus adhatodifolia	100, 200, and 300 mg kg^{-1} IBA	-	8.0	Santos et al. (2011)
Ficus citrifolia	100, 200, and 300 mg kg^{-1} IBA	-	1.0	Santos et al. (2011)
Guazuma ulmifolia	100, 200, and 300 mg kg^{-1} IBA	-	2.0	Santos et al. (2011)
Hevea brasiliensis	5,000 mg L^{-1} IBA and 1,000 mg L^{-1} NAA	-	-	Monteiro et al. (2015)
Inga marginata	100, 200, and 300 mg kg^{-1} IBA	-	0.0	Santos et al. (2011)
Inga vera	100, 200, and 300 mg kg^{-1} IBA	-	0.0	Santos et al. (2011)
Lecythis pisonis	2,000, 4,000, 6,000, and 8,000 mg kg^{-1} IBA	53	-	Bernardes et al. (2020)
Maclura tinctoria	100, 200, and 300 mg kg^{-1} IBA	-	0.0	Santos et al. (2011)
Magnolia ovata	100, 200, and 300 mg kg^{-1} IBA	-	0.0	Santos et al. (2011)
Maytenus evonymoides	3,000 and 6,000 mg L^{-1} IBA	23	8.3	Parajara (2015)
Miconia albicans	-	-	<13.3	Sousa et al. (2015)
Miconia ibaguensis	-	-	<86.7	Sousa et al. (2015)
Myrciaria dubia	200 mg L^{-1} IBA and ANA	-	<80.0	Oliva Cruz (2005a)
Myrciaria dubia	200 and 400 mg L^{-1} IBA + NAA	-	<55.6	Oliva Cruz (2005b)
Myrciaria dubia	200 mg L^{-1} IBA	-	<58.0	Delgado & Yuyama (2010)
Myrciaria dubia	1,000, 2,000, 3,000, 4,000, and 5,000 mg L^{-1} IAA, IBA, and NAA	-	<12.0	Silva et al. (2010)
Myrciaria dubia	500, 1,000, and 2,000 mg kg^{-1} IBA	<20	<38.3	Lima et al. (2020)
Myrciaria dubia	-	<30	<33.3	Lima et al. (2020)
Piper arboreum	1,000, 2,000, and 4,000 mg L^{-1} IBA	<89	<79.0	Rios & Ribeiro (2014)
Psidium cattleyanum	1,000 mg L^{-1} IBA	<1	5.2	Schwengber et al. (2000)
Psidium guajava	4,000 mg L^{-1} IBA	<62	<70.6	Samaan et al. (2010)
Psidium guajava	-	<83	-	Qadri et al. (2018)
Redhia gardneriana	1,000, 3000, 5,000, and 7,000 mg L^{-1} IBA	-	30.0	Franco et al. (2007)
Rollinia emarginata	1,000, 2,000, and 3,000 mg L^{-1} IBA	40	0.0	Bettiol Neto et al. (2006)
Rollinia emarginata	1,000, 3,000, 5,000, and 7,000 mg L^{-1} ,IBA	<42	<19.0	Scaloppi Junior & Martins (2003)
Rollinia mucosa	1,000, 3,000, 5,000 and 7,000 mg L^{-1} IBA	<37	<7.0	Scaloppi Junior & Martins (2003)
Rollinia mucosa	1,000, 3,000, 5,000, and 7,000 mg L^{-1} IBA	42	0.5	Scaloppi Junior (2007)
Rollinia rugulosa	2,000, 1,000, and 6,000 mg L^{-1} IBA and NAA	-	<4.0	Pinto et al. (2003)
Rollinia sp.	1,000, 2,000, and 3,000 mg L^{-1} IBA	83	43.0	Bettiol Neto et al. (2006)
Rollinia sp.	100, 200, and 400 mg L^{-1} IBA	0	0.0	Scaloppi Junior (2007)
Salix humboldtiana	100, 200 and 300 mg kg^{-1} IBA	-	<88.0	Santos et al. (2011)
Rinorea guianensis	100, 200 and 300 mg kg^{-1} IBA	-	2.5	Santos et al. (2011)
Spondias mombin	500, 1,000, 1,500 and 2,000 mg L^{-1} IBA	-	<25.0	Souza & Lima (2005)
Spondias purpurea	-	-	<33.0	Lima et al. (2002)
Spondias sp.	500, 750 and 1,000 mg L^{-1} IBA	-	52.7	Lima et al. (2002)
Spondias tuberosa	-	<69	<33.3	Paula et al. (2007)
Rinorea guianensis	100, 200 and 300 mg kg^{-1} IBA	-	0.0	Santos et al. (2011)
Theobroma cacao	1,000, 3,000, 6,000 and 9,000 mg kg^{-1}	<86	<93.3	Leite & Martins (2007)
		Basal sprouts		
Aniba rosaeodora	2,000, 4,000, and 6,000 mg L^{-1} IBA	91	66.0	Sampaio et al. (1989)
Calophyllum brasiliense	100, 1,000, 50,000, and 10,000 mg L^{-1} IBA	100	83.3	Ciriello & Mori (2015)
Calophyllum brasiliense	6,000 mg L^{-1} IBA	<90	65.0	Kratz et al. (2016)
		Sprouting of detached branches kept in a greenhouse		
Myrciaria dubia	500, 1,000, and 2,000 mg kg^{-1} IBA	<38	<28.3	Lima et al. (2020)
Myrciaria dubia	-	<33	<30.0	Lima et al. (2020)

[1]IBA, indole butyric acid; NAA, naphthaleneacetic acid; and IAA, indole acetic acid. [2]Efficiency of rooting. -, No information available.

between rootstock and scion, the efficiency of the technique should be evaluated considering physiological qualities, application environment, and type of grafting (Rodriguez et al., 2015).

With purposes similar to those of grafting, layering is also used to rescue fruit trees. This is another technique for plant propagation, in which the new plant remains at least partially attached to the mother plant while forming new roots. Even though the method has a low operational efficiency and a high cost, it is frequently used on native tree species, mainly air layering, which causes little damage to the mother tree (Anandhanambi et al., 2016). The air layering technique is used to produce flowers, fruits, and seeds and has been successfully applied to Amazon tree species such as *Anacardium occidentale* L., *Bixa orellana* L., *Psidium guajava* L., and *C. brasiliense*. However, as the capacity to form adventitious roots decreases with physiological age, the maturation degree of the plant or of the part to be rescued must be considered (Wendling et al., 2014b).

Another technique is mound layering, used in fruit growing to produce plants and rootstocks of native tree species such as *Acca sellowiana* (O. Berg) Burret, *Psidium cattleyanum* Sabine, *P. chinensis*, *Psidium cujavillus* Burm.f., *Psidium friedrichsthalianum* Nied., and *P. guajava*, among others (Table 5). It consists of covering the shoot base with soil to induce adventitious

Table 4. Vegetative rescue using crown sprouts by the grafting technique in Amazon tree species.

Species	Grafting technique	Survival (%)	Reference
Bertholletia excelsa	Budding	82	Müller (1982)
Bertholletia excelsa	Top cleft	<80	Carvalho & Nascimento (2016)
Bertholletia excelsa	Budding	100	Ferreira (2019)
Couepia edulis	Budding and top cleft	100	Yuyama et al. (2013)
Hymenaea courbaril	Top cleft	9	Mendes (2019)
Handroanthus heptaphyllus	Top cleft	80	Mendes (2019)
Swietenia macrophylla	Top cleft	76	Mendes (2019)

Table 5. Vegetative rescue using crown and basal sprouts by air and mound layering in Amazon tree species.

Species	Origen	Growth regulator(1)	Efficiency(2)	Survival (%)	Reference
		Air layering			
Bixa orellana	Basal sprouts	1,000 mg L^{-1} IBA	100.0	100	Mantovani et al. (2007)
Bixa orellana	Basal sprouts	4.92 mM IBA	100.0	100	Mantovani et al. (2010)
Anacardium occidentale	Crown sprouts	250 mg L^{-1} IBA	100.0	<89	Almeida et al. (1990)
Anacardium occidentale	Crown sprouts	250 mg L^{-1} IBA	100.0	<86	Almeida et al. (1991)
Calophyllum brasiliense	Crown sprouts	500, 1,000, and 2,000 mg L^{-1} IBA	<16.7	<83	Leite et al. (2007)
Psidium guajava	Crown sprouts	1,000 mg L^{-1} IBA, NAA, and PBZ	<71.2	41	Ullah et al. (2005)
Psidium guajava	Crown sprouts	1,000, 2,000, 3,000, 4,000, and 6,000 mg L^{-1} IBA and NAA	91.6	-	Anandhanambi et al. (2016)
Psidium guajava	Crown sprouts	1,000, 2,000, 3,000, and 4,000 mg L^{-1} IBA	<33.3	100	Manga et al. (2017)
Psidium guajava	Crown sprouts	1,500, 3,000, and 4,500 mg L^{-1} IBA	100.0	-	Naithani et al. (2018)
Psidium guajava	Crown sprouts	5,000 and 7,500 mg L^{-1} IBA + NAA	82.6	-	Deshlehra et al. (2019)
		Mound layering			
Acca sellowiana	Basal sprouts	-	<36.1	-	Fachinello & Nachtigal (1992)
Acca sellowiana	Basal sprouts	-	100.0	-	Mielke et al. (1994)
Psidium cattleyanum	Basal sprouts	5,000 mg L^{-1} IBA	33.3	18	Mishra et al. (2007)
Psidium chinensis	Basal sprouts	5,000 mg L^{-1} IBA	100.0	96	Mishra et al. (2007)
Psidium cujavillus	Basal sprouts	5,000 mg L^{-1} IBA	84.4	75	Mishra et al. (2007)
Psidium friedrichsthalianum	Basal sprouts	5,000 mg L^{-1} IBA	8.8	7	Mishra et al. (2007)
Psidium guajava	Basal sprouts	3,000, 5,000, 7,000, and 9,000 mg L^{-1} IBA	82.3	73	Rymbai (2009)
Psidium guineense	Basal sprouts	5,000 mg L^{-1} IBA	52.3	48	Mishra et al. (2007)

(1)IBA, indole butyric acid; NAA, naphthaleneacetic acid; and PBZ, paclobutrazol. (2)Efficiency of rooting. -, No information available.

rooting from adventitious and dormant buds, aiming at more juvenile parts and the rooting capacity of the plant (Naithani et al., 2018).

Despite these results, there is still the need for further research on the techniques to be used for each species.

5. Vegetative propagation

Vegetative propagation occurs after genotype rescue, aiming to produce several genetically identical copies on a commercial or noncommercial scale, also known as cloning (Stuepp et al., 2018). In clonal forestry, cloning has played an important role in increasing the productivity and quality of *Eucalyptus* spp. (Xavier et al., 2021). However, the recommended cloning techniques differ according to species and purpose, considering the basic principle of propagule maturation, as well as the distinct ecological and biological characteristics of native species compared with non-native or commercially cultivated varieties. Therefore, effective propagation strategies for native trees must account for their unique growth habits, genetic diversity, and ecological roles, which often involves adapting or developing specialized methods that align with the conservation goals and ecological contexts of these species.

In this scenario, the successful propagation of native trees requires a comprehensive approach that integrates detailed knowledge of the natural history of each species when using specific propagation techniques (Xavier et al., 2021). This type of information is readily available for species as *T. cacao* and *H. brasiliensis*, which have been used in clonal forestry over several years. Clonal plantations of *T. cacao*, for example, were first implemented in the 1930s–1940s, being replaced by biclonal hybrids, and later returned to substitute stands susceptible to witches' broom (Soares, 2019). *Hevea brasiliensis*, used for seed and rubber production, has been subjected to cuttings trials since the 1950s (Mendes, 1959a; Castro et al., 1984). However, in general, the vegetative propagation of native tree species is still little explored despite the rooting potential observed in several families (Stuepp et al., 2018), except in the cases of the already mentioned *H. brasiliensis* and *T. cacao* and of *P. guajava* (Deshlehra et al., 2019).

Although cloning is a key alternative for species presenting difficulty in propagating, there is still the need for more researches about the technical and economic viability of vegetative propagation under field conditions. This knowledge is essential considering the two main purposes of the vegetative propagation of native tree species: environmental, to restore degraded ecosystems; and forestry production, to obtain wood and non-wood products (Sales, 2022).

5.1 Vegetative propagation using juvenile parents (seedlings)

Seedlings are often used to obtain propagules of native tree species due to their juvenile nature, providing a greater rooting efficiency and root vigor than mature propagules (Wendling et al., 2014b). However, to maintain genetic diversity, propagules should be obtained from genetically different mother trees, preferably from different forest fragments, as well as collected from multiple parent trees to avoid seedlings from the same parent (Xavier et al., 2021).

When applying a plant selection technique, it is important to consider phenotypic performance, which is generally evaluated in the adult stage of a tree. In this case, prior knowledge is not essential since young plants can be used as an important alternative, especially when genetically improved seeds are available or when it is desired to maintain pruned seedlings under nursery conditions, a common technique in *Pinus* spp. (Stuepp et al., 2018).

In the literature, the greater juvenility of the used propagules has resulted in a high success rate in the vegetative propagation of native tree species, especially through cuttings (Table 6).

5.2 Vegetative propagation using adult mother trees

The most common techniques for the vegetative propagation of native tree species are cuttings, mini-cuttings, and grafting. However, the propagules produced using these techniques differ in productivity and physiological quality, which affects their multiplication potential and root and vegetative vigor (Stuepp et al., 2018).

Cuttings (clonal hedges) can be used for plant propagation, requiring the implementation and appropriate management of the clonal hedges, as well

Table 6. Application of the cuttings and mini-cuttings technique as a method of mass propagation in Amazon tree species.

Species	Propagule[(1)]	Growth regulator[(2)]	Survival (%)	Efficiency[(3)]	Reference
Juvenile plants (seedlings)					
Apuleia leiocarpa	Juvenile	4,000 mg kg^{-1} IBA	42	-	Freire et al. (2020)
Apuleia leiocarpa	Juvenile	0, 1,000, 2,000, and 4,000 mg kg^{-1} IBA	25	31.3	Freire et al. (2020)
Calophyllum brasiliense	Juvenile	100, 1,000, 3,000, 5,000, 7,000, and 10.000 mg L^{-1} IBA	<75	<75.0	Ciriello & Mori (2015)
Carapa guianensis	Juvenile	4,000 and 6,000 mg L^{-1} IBA	-	<83.3	Rosa (1993)
Hevea brasiliensis	Juvenile	-	-	100.0	Muzik & Cruzado (1956)
Hevea brasiliensis	Juvenile	-	-	30.0	Muzik & Cruzado (1958)
Hevea brasiliensis	Juvenile	-	-	>85.0	Mendes (1959a)
Hevea brasiliensis	Juvenile	200 mg L^{-1} IBA	100	<66.6	Castro et al. (1984)
Hymenaea courbaril	Juvenile	4,000 mg kg^{-1} IBA	74	<3.0	Freire et al. (2020)
Himatanthus sucuuba	Juvenile	1,000 and 3,000 mg L^{-1} IBA	<92	<93.3	Vasconcelos et al. (2020)
Rollinia mucosa	Juvenile	1,000, 3,000, 5,000, and 7,000 mg L^{-1} IBA	<95	<40.5	Scaloppi Junior (2007)
Rollinia sp.	Juvenile	100, 200, and 400 mg L^{-1} IBA	16.2	1.5	Scaloppi Junior (2007)
Schizolobium parahyba var. *amazonicum*	Juvenile	2,000 and 4,000 mg L^{-1} IBA	-	<80.1	Rosa & Pinheiro (2001)
Schizolobium parahyba var. *amazonicum*	Juvenile	2,000 and 4,000 mg L^{-1} IBA	-	<83.1	Rosa & Pinheiro (2001)
Schizolobium parahyba var. *amazonicum*	Juvenile	3,000 mg L^{-1} IBA	44	<51.3	Lima & Ohashi (2016)
Schizolobium parahyba var. *amazonicum*	Juvenile	2,000 and 3,000 mg L^{-1} IBA	<45	<90.0	Lima et al. (2018)
Sclerolobium paniculatum	Juvenile	2,000, 4,000, and 6,000 mg L^{-1} IBA	<62	<60.0	Rosa (1997)
Theobroma cacao	Juvenile	6,000 mg L^{-1} IBA	100	100.0	Sodré (2007)
Clonal hedge					
Cariniana estrellensis	Adult	2,000 and 6,000 mg L^{-1} IBA	100	<90.0	Hernandez et al. (2013)
Hevea brasiliensis	Adult	-	-	<90.0	Tinley & Garner (1960)
Swietenia macrophylla	Adult	-	<70	<62.5	Azad & Matin (2015)
Schizolobium parahyba var. *amazonicum*	Juvenile	8,000, 16,000, 24,000, and 32,000 mg L^{-1} IBA	100	<88.9	Dias et al. (2015)
Theobroma cacao	Adult	6,000 mg L^{-1} IBA	100	100.0	Faria & Sacramento (2003)
Mini-clonal hedge					
Calophyllum brasiliense	Juvenile	2,000, 4,000, and 8,000 mg L^{-1} IBA	-	<95.8	Silva et al. (2010)
Cariniana estrellensis	Juvenile	1,000, 2,000, 3,000, and 4,000 mg L^{-1} IBA and NAA	100	<83.3	Gatti et al. (2011)
Cedrela fissilis	Juvenile	-	100	100.0	Xavier et al. (2003)
*Calycophyllum spruceanu*m	Juvenile	1,000, 2,000, and 3,000 mg L^{-1} IBA and ANA	100	100.0	Gatti (2002)
Cordia trichotoma	-	1,000 mg L^{-1} IBA	<37	<26.6	Kielse et al. (2015)
Handroanthus heptaphyllus	Juvenile	8,000 mg L^{-1} IBA	100	<93.8	Oliveira et al. (2015a)
Handroanthus heptaphyllus	Juvenile	2,000, 4,000, 6,000, and 8,000 mg L^{-1} IBA	95	100.0	Oliveira et al. (2015b)
Plathymenia foliolosa	Juvenile	2,000 mg L^{-1} IBA	<88	<37.3	Neubert (2014)
Plathymenia foliolosa	Juvenile	20,000, 40,000, and 60,000 mg L^{-1} IBA	84	-	Neubert (2014)
Psidium cattleyanum	Juvenile	-	100	<95.8	Altoé et al. (2011)
Psidium guineense	Juvenile	-	100	100.0	Altoé et al. (2011)
Psidium guajava	Juvenile	-	100	100.0	Altoé et al. (2011)
Schizolobium parahyba var. *amazonicum*	Juvenile	8,000, 20,000, 40,000, and 60,000 mg L^{-1} IBA	<77	<65.0	Souza (2015b)
Schizolobium parahyba var. *amazonicum*	Juvenile	20,000, 40,000, and 60,000 mg L^{-1} IBA	<75	<70.0	Souza (2015b)
Theobroma cacao	Juvenile	1,500, 3,000, 4,500, and 6,000 mg L^{-1} IBA	-	<95.0	Soares (2019)

[(1)]Juvenile, seminal stump propagule formed from seedlings; and Adult, clonal stump propagule formed with clones from adult mother trees. [(2)]IBA, indole butyric acid; and NAA, naphthaleneacetic acid. [(3)]Efficiency of rooting. -, No information available.

as the quality of the vegetative propagules obtained. However, clonal hedges are not widely used for native tree species as most are still in the early stages of clonal forestry (Table 6).

For *H. brasiliensis* cuttings are a mass propagation technique that produces plants with a higher morphological quality and in a shorter time than the grafted ones, being an alternative for the production of propagules for grafting (Monteiro et al., 2015). Other species, including *Cariniana estrellensis* (Raddi) Kuntze, *H. brasiliensis*, *S. macrophylla*, *S. parahyba* var. *amazonicum*, and *T. cacao*, have been managed using clonal hedges, aiming to produce plants for the formation of commercial plantations or as a strategy for recovering degraded areas (Azad & Matin, 2015). In this sense, clonal hedges are more productive than vegetative rescue techniques, allowing of a high propagule production with an adequate nutritional and phytosanitary management. However, although cuttings do not require covered structures as mini-clonal gardens, it is necessary to consider the particularities and objectives of each species (Xavier et al., 2021).

The mini-cuttings technique (mini-clonal hedge) is an evolution of the cuttings technique (clonal hedges) that offers the nutritional and phytosanitary control of the generated propagules, reducing production area, rooting, and acclimatization period, in addition to decreasing the use of plant growth regulators (Kielse et al., 2015). The efficiency of this technique depends on the maturity of the ministumps, with higher rooting rates for juveniles compared with adults (Wendling et al., 2014a). In vegetative propagation studies, several species have been managed in mini-clonal hedges, such as *C. brasiliense*, *C. estrellensis*, *C. fissilis*, *C. spruceanum*, *C. trichotoma*, *H. heptaphyllus*, *P. cattleyanum*, *Psidium guineense* Sw., *P. guajava*, *Plathymenia foliolosa* Benth., *S. parahyba* var. *amazonicum*, and *T. cacao* (Table 6). The aim of these researches is to produce plants for the timber and fruit sectors, as well as data to be used in strategies for environmental restoration and adaptation (Oliveira et al., 2015a). Despite being used experimentally, mini-cuttings have shown positive results for propagating Amazon tree species (Stuepp et al., 2018); however, there is little genetic material available.

Grafting is used for the rescue of superior materials and for mass propagation, mainly in fruit trees, maintaining the maturity of the propagules and anticipating flowering, which can be reduced in some cases (Borelli, 2016; Mendes, 2019). Since the beginning of the 20th century, this technique has been the main one used for the vegetative propagation of *H. brasiliensis*, with initial tests resulting in up to an 81% efficiency. The most commonly used method is the budding technique with green stems, in which the buds for grafting are obtained from clonal hedges and mini-hedges are grafted onto seedling rootstocks (Borelli, 2016). The grafting technique has also been successful in other Amazon tree species, including *B. excelsa*, *Genipa americana* L., *M. dubia*, *S. tuberosa*, and *T. grandiflorum* for the mass production of plants for fruits and seeds (Table 7). Grafting can also be used to form orchards and produce plants with characteristics similar to those of seminal plants, as observed for *Araucaria angustifolia* (Bertol.) Kuntze (Wendling et al., 2017). In addition, the technique has been widely used in vegetative rescue for timber and environmental purposes, mainly due to its low cost, possible variation based on rootstocks, and direct application in the field, without the need for special structures such as those required by cuttings (Xavier et al., 2021).

A complementary alternative to traditional propagation techniques is in vitro propagation (micropropagation), which is used for the rescue, rejuvenation, and clonal multiplication of tree species by propagating explants collected in the field or in a contaminant-free greenhouse (Xavier et al., 2021). According to the same authors, studies on micropropagation seek to solve problems related to fungal and bacterial contamination, phenolic oxidation, and lack of morphogenic response in explants.

In micropropagation, after in vitro establishment, explants can be multiplied, elongated, rooted in vitro or ex vitro, and acclimatized in an ex vitro environment, encouraging the implementation of clonal forestry programs for tree species that are difficult to root and of great commercial interest (Silva et al., 2020a). Despite this, most studies on this technique are exploratory and incipient, restricted to initial stages, including in vitro establishment and multiplication, which are mainly used for the development of micropropagation protocols. Among the species with two or more studies on micropropagation, stand out *Caesalpinia pyramidalis* Tul., *C. fissilis*, *C. trichotoma*, *Erythrina velutina* Willd., *Guazuma crinita* Mart., *Hancornia* *speciosa* Gomes, *Myracrodruon urundeuva* Allemão, *S. macrophylla*, and *S. parahyba* var. *amazonicum* (Table 8).

The micropropagation of native tree species can be challenging due to the variable responses of each species and genotype to in vitro cultivation, as well as to the possibility of contamination by microorganisms. It should be added that the efficiency of micropropagation depends on several factors, including the type of explant and system used, physicochemical conditions, species, and collection period. In the literature, most studies have been carried out using seedling explants and may require adjustments in the micropropagation phases (Franco et al., 2006; Bonfá, 2019).

For native tree species, the most common explants are apical and nodal segments (axillary buds), generally obtained from seeds germinated in vitro due to the difficulty of acquiring adult plant materials free of contaminants and responsive to in vitro cultivation (Reis et al., 2007b; Gutiérrez et al., 2013). Nodal segments are more efficient for the propagation of woody species because of their higher number of pre-existing axillary buds, being more commonly used, together with other types of meristems, due to a greater material availability or a lower sensitivity to disinfestation (Costa et al., 2010; Gomes et al., 2010). However, embryos and seed tissues have also been used for micropropagation in native tree species such as *S. parahyba* var. *amazonicum*. Although it can be advantageous, the use of these explants can limit the cloning of superior materials considering their genetic recombination (Cordeiro et al., 2002).

The main micropropagation systems for tree species include the proliferation of axillary buds, organogenesis, and somatic embryogenesis, and, in some cases, callogenesis, processes that can be expensive due to genetic variability and the consequent need for method adaption to each species. For Amazon tree species, for example, the proliferation of axillary buds is the most used system, being obtained from nodal, apical, cotyledonary, and intercotyledonary segments according to Xavier et al. (2021), cited in Table 8.

The organogenesis and somatic embryogenesis systems are promising tools to be applied in the forestry area, including in vitro germplasm conservation and clonal forestry programs. However, there is still little research on native tree species, requiring the development of more efficient protocols for varying species (Xavier et al., 2021). Somatic embryogenesis, for example, has been shown to be a promising technique for *A. sellowiana*, *Didymopanax morototoni* Decne. & Planch., and *H. brasiliensis*, and, therefore, should be further developed in future research (Franco et al., 2006; Soares et al., 2007; Booz et al., 2009).

Table 7. General application of grafting for vegetative propagation (multiplication) of Amazon tree species.

Species	Propagule	Grafting technique	Survival (%)	Reference
Bertholletia excelsa	Clonal hedge	Budding	58.7	Baldoni et al. (2017)
Genipa americana	Crown	Top cleft	100.0	Prado Neto (2006)
Hevea brasiliensis	Crown	Approach	100.0	Mendes (1959b)
Hevea brasiliensis	Crown	Budding	95.0	Cardoso (1961)
Hevea brasiliensis	Crown	Top cleft	74.0	Lemos Filho (1991)
Hevea brasiliensis	Mini-clonal hedges	Budding and top cleft	<73.0	Borelli (2016)
Handroanthus chrysotrichus	Crown	Top cleft	<33.3	Simões (2017)
Handroanthus heptaphyllus	Crown	Top cleft	<83.3	Simões (2017)
Handroanthus roseo-albus	Crown	Top cleft	<38.8	Simões (2017)
Myrciaria dubia	Crown	Top cleft	<89.3	Moreira Filho & Ferreira (2009)
Myrciaria dubia	Crown	Budding and top cleft	<96.6	Rodriguez et al. (2015)
Psidium guajava	Crown	Top cleft	<63.0	Robaina et al. (2015)
Spondias tuberosa	Crown	Budding	78.0	Pedrosa (1991)
Theobroma grandiflorum	Crown	Budding and top cleft	<95.0	Venturieri et al. (1986)

Table 8. Studies of in vitro propagation applied to Amazon tree species.

Species	Explant	Micropropagation system	Reference
Acca sellowiana	Zygotic embryos	Somatic embryogenesis	Booz et al. (2009)
Amburana acreana	Nodal segments	Axillary bud proliferation	Fermino Junior & Scherwinski-Pereira (2012)
Anadenanthera colubrina var. *cebil*	Plantlets	Axillary bud proliferation	Nepomuceno et al. (2009)
Aniba rosaeodora	Zygotic embryos; apical and axillary bud	Axillary bud proliferation	Handa et al. (2005)
Aspidosperma ramiflorum	Apical segments	Axillary bud proliferation	Hubner et al. (2007)
Aspidosperma polyneuron	Nodal segments	Axillary bud proliferation	Ribas et al. (2005)
Cabralea canjerana	Nodal segments	Axillary bud proliferation	Rocha et al. (2007)
Caesalpinia pyramidalis	Epicotyl; leaf	Axillary bud proliferation	Rodrigues et al. (2017)
Calophyllum brasiliense	Nodal segments	Axillary bud proliferation	Santos et al. (2006)
Cedrela fissilis	Apical, nodal, and cotyledon segments	Axillary bud proliferation	Bonfá (2019)
Cedrela odorata	Apical segments	Axillary bud proliferation	Saldanha (2010)
Celtis sp.	Nodal segments	Axillary bud proliferation	Sato et al. (2001)
Cordia trichotoma	Plantlets	Axillary bud proliferation	Heberle (2010)
Didymopanax morototoni	Root; stem; leaf nodule; cotyledon leaf	Somatic embryogenesis	Franco et al. (2006)
Erythrina velutina	Plantlets	Axillary bud proliferation	Costa et al. (2010)
Guazuma crinita	Root; petioles	Organogenesis	Maruyama et al. (1997)
Hancornia speciosa	Plantlets	Organogenesis	Soares et al. (2007)
Hancornia speciosa	Nodal segments	Axillary bud proliferation	Sá et al. (2012)
Himatanthus sucuuba	Leaf and nodal segments	Somatic embryogenesis	Vasconcelos (2020)
Handroanthus impetiginosus	Epicotyl	Axillary bud proliferation	Larraburu et al. (2012)
Maclura tinctoria	Nodal segments	Axillary bud proliferation	Gomes et al. (2010)
Miconia sp.	Nodal segments; leaf	Organogenesis	Cid et al. (1997)
Mimosa caesalpiniaefolia	Apical and nodal segments	Axillary bud proliferation	Oliveira et al. (2007)
Myracrodruon urundeuva	Apical and nodal segments	Axillary bud proliferation	Silva et al. (2020a)
Moringa oleifera	Plantlets; stem apices	Axillary bud proliferation	Cysne (2006)
Psidum guajava	Nodal segments	Axillary bud proliferation	Kadam et al. (2017)
Plathymenia reticulata	Nodal and cotyledon segments	Axillary bud proliferation	Moura et al. (2012)
Swietenia macrophylla	Apical and nodal segments	Axillary bud proliferation	Lameira et al. (2005)
Swietenia macrophylla	Epicotyl	Callogenesis(1)	Brunetta et al. (2006)
Schizolobium parahyba var. *amazonicum*	Nodal segments	Axillary bud proliferation	Cordeiro et al. (2006)
Schizolobium parahyba var. *amazonicum*	Apical, nodal, and cotyledon segments	Callogenesis(1)	Reis et al. (2007a)
Schizolobium parahyba var. *amazonicum*	Apical, nodal and cotyledon segments; root	Callogenesis(1)	Souza (2015a)
Stryphnodendron polyphyllum	Cotyledon segments	Axillary bud proliferation	França et al. (1995)
Sebastiania schottiana	Nodal segments	Axillary bud proliferation	Deschamps & Pinto (1995)
Tapirira guianensis	Nodal and cotyledon segments; epicotyl	Axillary bud proliferation	Gutiérrez et al. (2013)
Theobroma grandiflorum	Floral bud	Axillary bud proliferation	Ferreira et al. (2009)

(1)Disorganized development of cells, without organ formation.

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6. Clonal forests and future perspectives

In the Amazon region, despite the potential of native tree species for clonal forestry, the *Eucalyptus* genus is the main one used, with relevance in the paper, cellulose, wood, and biomass energy sectors (Almeida & Vieira, 2022). To date, the forestry sector has only promoted a few native species, such as *H. brasiliensis* and *P. guajava* (Stuepp et al., 2018).

In general, research on the clonal forestry of native tree species is at initial levels, being concentrated in forestry research centers or private companies, often facing challenges such as an inadequate genetic selection and short-duration projects, which hinder long-term advancements and the field application of clonal methodologies. Therefore, there is a pressing need for a more comprehensive study and integrated approaches to enhance the practical implementation of clonal forestry for Amazon tree species.

Although progress has been made in clonal forestry for these species, with selected materials and field assessments showing promising results, the dissemination of these advancements still remains insufficient (Stuepp et al., 2018). The limited distribution of information is often attributed to inadequate publication channels, restricted access to research findings, and the lack of structured platforms for knowledge transfer. Consequently, the potential benefits of these advancements are not fully realized or applied in wider forestry practices. Therefore, addressing these challenges is crucial for accelerating the adoption and refinement of clonal forestry techniques, especially using Amazon tree species.

Even though there is little information on the field performance of these native species, some of them have been identified as having potential for clonal forestry, such as *C. brasiliense*, *E. estrellensis*, *C. spruceanum*, and *C. trichotoma*, showing that vegetative propagation is in fact viable.

Hevea brasiliensis, for example, is a native tree species used in clonal forestry that has been the subject of research since the beginning of the 20th century. The first studies evaluated the compatibility of juvenile grafts and seedlings rootstocks, while subsequent tests were carried out on clones produced by cuttings, with the aim of increasing latex production and pest tolerance (Stuepp et al., 2018). The clonal forestry of the species has been successful in many regions of the world, increasing average stand productivity to 2,500 kg ha^{-1} of latex per year (Leonello et al., 2012). In addition, breeding programs have been showing interest in wood quality, aiming the commercialization of timber to replace old plantations (Muzik & Cruzado, 1956, 1958; Mendes, 1959a; Tinley & Garner, 1960).

In the case of *P. guajava*, even though the clonal propagation of the species has been carried out for centuries, significant advances have only been reported in the last 100 years, including pest/disease management techniques, mass propagation protocols, access to growth regulators, knowledge of juvenile propagation, advances in knowledge of chimeras, micropropagation, and the use of vegetative propagation to prevent diseases caused by viruses and other pathogens (Deshlehra et al., 2019).

Another Amazon tree species with potential for clonal forestry is *S. parahyba* var. *amazonicum* due to the quality of its wood used in the plywood industry, as well as to its productive potential and viability for cultivation in the region (Sales et al., 2024). Furthermore, it is the main tree species cultivated in pure stands for timber purposes in the Brazilian Amazon (Silva et al., 2020b). However, although vegetative propagation protocols for cuttings and micropropagation have been used to produce plants of this species for commercial plantations, the applied techniques still need to be evaluated in the field (Sales, 2022).

To produce plants for timber and environmental purposes, viable and low-cost techniques include direct field cuttings and grafting, which are potentially useful for forming orchards for the production of improved seeds (Sales, 2022). Considering this purpose, *T. cacao* and *T. grandiflorum* are Amazon fruit tree species of interest in clonal forestry, which is important for breeding programs that have been focusing on fruit and seed production (Almeida et al., 2014).

According to the studied literature, native tree species have the potential to be used in clonal forestry for productive and environmental purposes. However, only a few of the species in the Amazon rainforest with potential for clonal forestry are currently being used in the forestry sector due to the lack of human, financial, technological, and structural resources, as well as to incipient knowledge of the silvicultural potential of each species (Stuepp et al., 2018). In this context, Xavier et al. (2021) highlighted the importance of preserving genetic diversity in the obtained plants while considering the particularities of each species and cultivation site to determine their suitability.

Concluding remarks

The exploration of vegetative propagation and clonal forestry in the Amazon region has highlighted the significant potential of these types of management to enhance both ecological restoration and commercial forestry. Techniques such as cuttings, grafting, and micropropagation are promising for the reproduction of native tree species with a high genetic fidelity. The mentioned approaches have improved the productivity and resilience of *H. brasiliensis* and *T. cacao*, also indicating the potential of species as *P. guajava* and *S. parahyba* var. *amazonicum*, which is still not fully known due to gaps in field testing and in practical applications.

Among the faced challenges are the limited genetic material, high costs, and a need for more detailed species-specific protocols. Furthermore, the current research and applications are often constrained by short-duration projects and an inadequate dissemination of their findings, hindering the execution of long-term studies necessary for the effective implementation of clonal forestry for native tree species of the Amazon region.

For an effective advancement, future efforts should focus on refining propagation techniques, expanding genetic research, and fostering a greater collaboration among stakeholders, research institutions, private companies, and local communities. Addressing these areas will be crucial for translating experimental successes into practical and large-scale applications, ensuring sustainable outcomes for both conservation and commercial goals in the Amazon.

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