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## **Modern breeding methods in forestry aimed at preserving genetic diversity**

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**Abstract.** This research is devoted to analysing the impact of modern breeding measures in forestry on the level of genetic diversity of forest tree species. It has been found that the main source of improved seed material for the genetic restoration of forests is base forest seed orchards. Aspects of the influence of determining factors – background pollination and the number of clones – on

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the indicators of genetic variability of progeny have been analysed in detail. The potential of background pollination in forest seed orchards in the context of a significant decrease in the effectiveness of breeding measures and a parallel increase in the level of genetic variability of progeny has been studied. An analysis of data on the minimum number of clones in seed orchards has been carried out based on the practical experience of other developed countries. The dynamics of clone variability in terms of fertility have been investigated. The potential impact of clonal selection on the genetic diversity of tree species, particularly in reducing it, has been identified. It has been confirmed that integrating the concept of family forestry, which involves the use of vegetative propagation techniques, into the breeding strategy significantly increases the level of genetic variability in progeny. The study has demonstrated that the multiple-population breeding system provides the optimal preconditions for synergising the process of long-term intensive breeding and preserving the gene pool of tree species. It has been determined that there is no negative impact on genetic diversity from implementing a complex of optimally planned breeding programs. At the same time, the potential for intensifying the quality of gene pool conservation in the process of forest ecosystem restoration through the use of improved seed material and clones in artificial orchards has been established. Special attention is given to the maintenance of *ex situ* – valuable genetic material in forest seed production facilities, including forest seed orchards, trial cultures, and clone archives of plus trees. Research has shown that the implementation of modern innovative solutions and scientific recommendations can minimise the loss of genetic diversity in forest tree species. The results can be applied in contemporary forestry breeding programs

**Keywords:** clonal technology; somatic embryogenesis; background pollination; *ex situ*; the number of clones

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## Introduction

The extensive management of forestry production processes, coupled with the destruction of forest ecosystems, the exhaustive use of technologically intensive methods to boost productivity, and the irreversible impacts of global climate change have necessitated a dynamic strategy in national forest management strategies. There is an urgent need to transition from traditional, exploitative practices towards organic, environmentally friendly approaches that ensure the preservation of genetic diversity. The creation of Kyrgyzstan's gene pool is the culmination of several generations of scientific endeavour. Targeted efforts on implementing global plant resources to enrich the republic's cultural flora have led to the creation of a genetic pool –

a material and intellectual national asset that supports the republic's economic development.

Population genetic studies of forest-forming timber plants provide the theoretical foundation for breeding programs aimed at conserving, optimising, protecting, and effectively reproducing the genetic potential of species within regional contexts (Skliar *et al.*, 2020; Tykhonova *et al.*, 2021). To maintain and enhance genetic diversity during reforestation, specific population-based approaches are employed. In general, there are two primary objectives in forest management: establishing sustainable orchards that are as diverse as natural populations and producing high-quality commercial timber. To optimally achieve the first

objective, plus tree selection is prioritised. This involves selecting the most productive trees within a population. The algorithm for achieving the second objective, producing high-quality timber, involves utilising the gene pool of populations or their complexes in the cultivation of artificial forests as a unified system. This systemic approach is the most promising in terms of preventing the degradation of the gene pool. Most contemporary scientists are focusing on exploring alternative technological approaches within the forestry breeding sector. These approaches aim to facilitate progress towards preserving the genetic sustainability of populations. In particular, there is a growing body of research concentrating on selection methods in forestry that prioritise the conservation of genetic diversity.

J.A. Karabaev *et al.* (2024) investigated the specific genetic components of natural systems that are subject to frequent changes in genotype due to evolutionary pressures. These pressures include genetic drift, mutation, migration, and natural selection. The researchers analysed the potential ecological risks to the adaptive capacity of biodiversity in forest ecosystems. They concluded that to mitigate the negative impacts of climate change, optimising breeding programs and implementing innovative technologies and advanced processes for preserving genetic diversity are of paramount importance. Several scientific publications by contemporary researchers have presented criteria for evaluating the effectiveness of breeding programs in forestry aimed at preserving genetic diversity. In particular, B.N. Shamshiev *et al.* (2020; 2024) focused on the effectiveness of developing sustainable forest ecosystems in Kyrgyzstan within the concept of their ecological and economic efficiency, justifying the need for implementing decarbonisation technologies and highlighting the main trends in the strategic development

of the industry. Z.H. Sarymsakov & D.K. Mama-djanov (2012) studied the main types of forests in Kyrgyzstan, the status of sustainable use programs, and opportunities for optimising the situation. Genetic diversity is assessed based on the effective population size, which considers the relatedness among individuals, as well as in the context of quantitative trait variability, evaluated using mathematical statistics, and the number of alleles identified using genetic markers (Integrated management of..., 2018).

Despite significant advancements in forestry breeding within contemporary scientific communities, the question of effectively stimulating the conservation of genetic diversity remains unresolved. This problem requires further investigation and the identification of optimal solutions. The primary goal is to conduct a comprehensive analysis of the potential of modern breeding practices in forestry within the context of preserving the level of genetic diversity in forest timber tree species.

### Materials and Methods

The research utilised statistical data from the National Statistical Committee of the Kyrgyz Republic (2024), strategic programme documents, and legal frameworks within the studied sector. Specifically, the research drew upon the Concept for the development of the forestry industry of the Kyrgyz Republic for the period up to 2040 (2019), as well as the Forest Code of the Kyrgyz Republic (1999), Law of the Kyrgyz Republic No. 53 “On Environmental Protection” (1999), Law of the Kyrgyz Republic No. 18 “On Specially Protected Natural Territories” (2011), Law of the Kyrgyz Republic No. 48 “On Biosphere Territories” (1999), Law of the Kyrgyz Republic No. 53 “On the Protection and Use of the Plant World” (2001), Resolution of the Kyrgyz Republic No. 131 “On Priorities for Conservation of Biological Diversity of the Kyrgyz Republic for the Period up to 2024 and

Action Plan for Implementation of Priorities for Conservation of Biological Diversity of the Kyrgyz Republic for 2014-2020” (2014), Regulations on the State Forest Service of the Kyrgyz Republic (2002).

Based on an abstract-logical conceptual approach, the conceptual apparatus has been refined, and theoretical generalisations and conclusions have been formulated. In the course of the research, to identify the specific mechanisms of modern selection methods, methods of statistical observation, comparison, analytical-structural grouping, and forecasting were employed. Statistical observation provided summarised data that accurately reflect the characteristics of the entire set of traits of the phenomenon under study. In the course of the research, to identify the specific dynamics of the development of selection systems in forestry, a comparison was made of key indicators of qualitative changes, including the minimum number of clones in forest seed orchards (FSOs), the quality of seed material and clones in artificial stands, and the *ex situ* conservation of genetic material in forest seed production sites (FSOs, trial crops, and clone archives of plus trees).

The analytical-structural grouping method was employed to identify the specific features of modern breeding approaches and to formulate proposals for optimising the management system to create optimal conditions for increasing the efficiency and appropriateness of regional forest use systems and preserving forest gene pools. Additionally, this method was used to identify priority vectors for optimising regional forest production systems based on “green” sustainable development and sustainable decarbonisation of technological processes, thereby laying the groundwork for the active practical application of breeding technologies in the system of management of forestry activities in Kyrgyzstan. Analytical-structural grouping enabled a systematic transition from

general abstract information about forestry selection technologies to the current situation in Kyrgyzstan’s forest management activities.

To identify the specific features, advantages, and effectiveness of certain decisions and approaches within the framework of the forest management selection concept, a forecasting method was used. Particular attention was paid to the need to consider potential obstacles in the practical implementation of the selection strategy. The research aims to comprehensively identify solutions in the modern forestry complex with a focus on economic efficiency and environmental safety, which, in synergy, form a system of circular sustainable economic activity in the forestry sector.

## Results

The contribution of forested areas to addressing current and future challenges in food security, poverty reduction, and environmental sustainability depends on the richness of both interspecific and intraspecific diversity of forest-forming tree species. Genetic diversity is essential for ensuring that forest-forming tree species can survive, adapt, and thrive in changing environmental conditions. It also supports the vitality of forests and provides resilience to stresses such as pests and diseases. Furthermore, genetic diversity is necessary for artificial selection, breeding, and domestication programs aimed at developing adapted varieties or strengthening beneficial traits. In many countries, the prospects for sustainable rural development will largely depend on the state of diversity within forest ecosystems and species.

The Kyrgyz Republic is characterised by relatively sparse forest cover. Forested areas in the country are represented primarily as mountain orchards with a diversity of valuable species. Nearly 90% of Kyrgyzstan’s forest ecosystems grow at altitudes between 800 and 3000 meters above sea level (National Statistical

Committee..., 2024). As stipulated by the National Forest Code, forest stands in the country serve as environmental protection areas and perform climate-regulating, sanitary-hygienic, eco-stabilising, and recreational functions. Results from practical research conducted by the Institute of Forestry at the National Academy of Sciences of Kyrgyzstan, in various natural and climatic conditions, confirm the ability of forests to mitigate the significant negative consequences of global climate change and their substantial water regulation function (Concept for the development..., 2019). The upward shift of forest ecosystems with increasing altitude potentially increases the vulnerability of many plant species to ecological and genetic impacts. The rate of climate change in the coming decades will outpace the rate at which forest ecosystems can adapt to new climatic conditions, leading to species extinction. Therefore, timely implementation of necessary forestry and selective breeding work forms the basis for preserving forest ecosystems within the concept of genetic diversity.

Research and scientific institutions in Kyrgyzstan are actively involved in modelling the potential evolution of the climatic optimum ranges for priority forest-forming tree species. A key feature of the models developed by the Institute of Water Problems at the National Academy of Sciences is the ability to dynamically track changes in the minimum altitude above sea level for juniper, common walnut, and spruce. It has been demonstrated that a 1.5°C increase in temperature stimulates fragmented upward migration, while a 4°C increase or more leads to a complete upward shift, causing a loss of ecological functions in forests (Integrated management of..., 2018). Therefore, the goal of maximising the preservation and development of forest ecosystems – selection – is consistently one of the priorities of sustainable forest management. Forest resource reproduction

combines measures to ensure forest restoration, afforestation, natural regeneration, and the creation of forest orchards (Adamenko *et al.*, 2023). A comprehensive approach to researching modern breeding solutions in forestry involves emphasising the industry's specific characteristics and shaping a model to prevent the reduction of genetic diversity among timber species. Such a process is envisioned as a complex, multi-stage production system. For maximally effective management, it is necessary to consider the specific features of the economic functioning of forestry within the concept of resource potential. In this case, particular importance is attached to ensuring high-level forest resource reproduction processes.

Most forest-forming tree species are wild and are managed within natural ecosystems, or are at a very primitive stage of selection or domestication compared to agricultural crops. Forest-forming tree species are typically long-lived, highly heterozygous organisms with well-developed natural mechanisms for maintaining high levels of intraspecific variation, such as high-speed distant crossbreeding and widespread dispersal of pollen and seed. These mechanisms, combined with native environments that often vary in time and space, contribute to the evolution of forest-forming trees into some of the most genetically variable organisms on Earth. Achieving sustainable forest management is anticipated to be possible through the implementation of closed-loop forestry technologies that utilise all available resource regeneration algorithms, employing organisational, production, socio-economic, ecological, and social factors. In particular, to reduce the risk of losing part of the genetic diversity, the introduction of a stabilisation period is deemed appropriate. The latter represents a specific time frame necessary for the implementation of a full set of compensatory measures to mitigate the destructive consequences

of long-term extensive forest management. The described strategy requires significant time and financial investments but is considered a necessary step for organic forestry production.

Climate change is impacting the resilience of ecosystems, which is particularly evident in the transition from traditional forestry to regenerative forestry. A reliable preventive measure to reduce the loss of genetic diversity in forest ecosystems is the creation of ecological buffer zones of 10%, which will help restore and preserve biodiversity (Salgotra & Chauhan, 2023). Additionally, the use of specialised selection methods is a necessary technological approach. All modern forest selection methods are based on:

1. The method of selecting the best plants for further propagation and use. This method falls under the category of analytical selection, where nothing new is created; instead, the best individuals from existing populations are utilised. Through intensive selection, it is possible to identify the best ecotypes, forms, and other variants within existing stands, as well as the best (plus trees), which can then be propagated and used in forestry seed production and afforestation to improve the quality of forests.

2. Hybridisation is an important selection method that enables the development of new forms and even species with a range of valuable traits and properties.

3. Polyploidy is a method of creating new plant forms by increasing the number of chromosomes several times beyond their haploid number.

4. Mutagenesis is a selection method that produces new plant forms through the application of various mutagens.

These methods are part of synthetic selection, which allows for the creation of new genetic material combinations and the construction of novel hereditary material combinations using various techniques. Following the National Development Strategy of the Kyrgyz Republic, the long-term development of the country should be framed within the concept of preserving unique natural ecosystems. The strategy aims to intensify the expansion of forest ecosystems, ensure the economic stability of the Republic's forestry sector, optimise the management paradigm for forests, and digitalise forestry infrastructure.

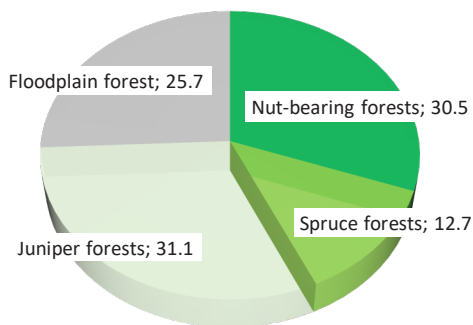
Forest ecosystems play a crucial role in mitigating adverse climate dynamics (Hoban *et al.*, 2021). Forests are considered the most effective natural way to regulate greenhouse gas concentrations in the atmosphere, highlighting the need to maximally preserve the species and genetic diversity of timber species in the forests of Kyrgyzstan, which function under the Republic's rather challenging climatic conditions (Table 1).

**Table 1.** Carbon stock in the forests of the Kyrgyz Republic

No.	Category	Forest lands	Other forest lands	Total
1	Above-ground carbon stock, million tonnes	13.3	0.3	13.6
2	Below-ground carbon stock, million tonnes	4	0.4	4.4
3	Carbon stock in dead plants, million tonnes	0.071	0.001	0.072
4	Carbon stock in forest floor, million tonnes	16.5	8.6	25.1
5	Carbon stock in soil, million tonnes	1,161	967	2,128
	Total	1,194.9	976.3	2,171.2

**Source:** Concept for the development of the forestry industry of the Kyrgyz Republic for the period up to 2040 (2019)

Forest diversification can be a powerful tool in the fight against climate change. Mixed forests accumulate carbon more rapidly than monocultures, meaning they can help achieve emissions reduction goals faster. The concept of carbon offsetting through forests is based on the idea that forests act as carbon sinks, absorbing and storing CO<sub>2</sub> from the atmosphere through photosynthesis. By conserving existing forests or restoring degraded areas, the amount of carbon stored in trees and soil can be increased, effectively offsetting emissions from other sources. As the data in Table 1 shows, the carbon stock of Kyrgyzstan's forests exceeds two million tonnes. There is a need to continue ensuring the ecological balance of forest ecosystems and preserving biodiversity. Kyrgyzstan's forest ecosystems are primarily represented by spruce, nut-bearing, floodplain, and juniper forests (Fig. 1).



**Figure 1.** Forests of the Kyrgyz Republic as of 2023, %

**Source:** National Statistical Committee of the Kyrgyz Republic (2024)

Despite the identified challenges in this research area, optimising forest management in Kyrgyzstan within the context of preserving genetic biodiversity has significant potential that can be fully realised with strong international support and investment opportunities.

The market-driven environment dictates that increasing profitability is the primary goal of forest management; therefore, the productive development of the selection sector to preserve genetic diversity is contingent upon maintaining adequate levels of economic performance (Cortés *et al.*, 2020). An adaptive forest management system aligned with the goals of sustainable development consists of a set of specific requirements, opportunities, and principles, as well as tools and technologies that contribute to enhancing the competitiveness of the sector and optimal resource utilisation.

Essential components of a sustainable development strategy for Kyrgyzstan's forestry sector, designed to maximally preserve genetic diversity, as proposed in the Concept for the development of the forestry industry of the Kyrgyz Republic for the period up to 2040 (2019), are considered to be the following:

- ◆ adapted progressive national scientific and legislative frameworks, the implementation of successful international experience and innovative solutions, as well as modelling and forecasting of dynamic situations;
- ◆ a technical and technological basis, which should allow for full analysis of information and statistical data, and integration of the latest technologies and concepts into the sector;
- ◆ a human resources basis that is aware of local needs and that makes the best use of regional potential to maximise development.

Innovative selection technologies in forestry involve identifying reliable characteristics of forest ecosystems, creating digital maps, and utilising GPS systems. A distinguishing feature of modern technologies is the active manipulation of plants at different stages of their growth cycle through a sequence of biological and technological treatments, which inevitably impacts productivity and efficiency in the forestry industry. Addressing the challenge of preventing genetic diversity loss requires preliminary

data collection and analysis, the creation of digital field maps, an effective decision-making system, and the development of technologies for forest management processes.

Geographic Information Systems (GIS) are currently positioned as the most effective tool for understanding and describing dynamic geographic environments. These systems find wide application in addressing many challenges associated with using spatially distributed information to ensure environmental safety and sustainable development of territories. GIS can be effectively used for analysing ecological and landscape monitoring data, creating digital maps, and assessing the dynamics and forecasting future trends in regional land use. GIS is a complex, multi-component system, a distinctive feature of which is the application of specific methods for analysing spatial data. These methods, in synergy with activities related to the formation, accumulation, processing, and presentation of spatially coordinated information, form the fundamental basis of GIS technology. One result of such integration is the emergence of geographic information mapping, which is an automated information and cartographic modelling of natural and socio-economic geosystems based on GIS and corresponding databases.

The use of GIS is associated with the enhancement of spatial-analytical operations in eco-landscape management for biodiversity conservation in forest areas, particularly buffer zones. Buffer zones in this context can include protective zones, sanitary protection zones, restricted zones, epidemiological zones, and others. Modern GIS tools allow for the automatic generation of buffer zones around objects of any type. Network analysis, aimed at defining three-dimensional spatial models, is also a popular aspect of GIS application in forest ecosystem management. Therefore, it can be asserted that the use of geographic information

technologies in the development and implementation of forest breeding programs allows for the effective evaluation of parameters in real-time, while simultaneously enabling predictive analytics. An advantage of using GIS in this context is the ability to integrate statistical methods, geographic information and digital modelling, and business graphics, which collectively allow for the identification of specific types of information as a basis for management decisions.

The integration and unification of diverse spatial information is achieved through GIS using data aggregation, conceptual communication, and extrapolation of processing results. The information processed in this way forms models of objects in the form of thematic maps, digital models of dynamics, vector images, and three-dimensional models, which significantly simplifies and optimises the selection process. A decrease in genetic variability compared to natural ecosystems is characteristic, as confirmed by numerous studies using biochemical and molecular genetics methods (Nonić & Šijačić-Nikolić, 2021). An assessment of changes in basic genetic indicators through special modelling of successive thinning in experimental cultures demonstrated a lack of negative dynamics in the concept of genetic diversity, even in the case of significant thinning intensity.

The population structure of forest species, shaped over a long evolutionary process, represents the most advantageous survival strategy for the species. Given that the population is its foundation, preserving the existing structural organisation of the species is positioned as preserving specific conditions for the self-reproduction of each population across generations. One of these conditions is the preservation of natural genetic variability within populations. To ensure genetic variability, it is necessary, based on modelling the population-chorological structure of a forest species, to identify at

least one genetic reserve in each population. Given that a population is an adapted and integrated dynamic system of individuals, the applied selection systems must ensure not only the preservation of all the diversity of these genotypes and their balance in a natural state but also the maintenance of the population's capacity for natural self-reproduction during exploitation and subsequent restoration (Mero *et al.*, 2023). Forestry selection programs, in general, should combine the following selection measures:

- ◆ developing a variety model optimal for a specific cultivation zone and target purpose;
- ◆ analysing and conducting detailed comparative studies of the original natural material and its artificially produced analogue for selection;
- ◆ choosing a selection method to obtain new forms of timber forest species;
- ◆ studying the progeny obtained, followed by the selection of samples that best meet the goals of the selection process;
- ◆ initial multiplication of the selected material;
- ◆ testing in various external conditions and different ecological settings;
- ◆ state zoning of the best varieties.

Forest regeneration should primarily occur naturally. To maximally preserve the genetic diversity of forest species populations, optimised breeding programs are also necessary. It is important to note that breeding programs based on individual selection should be carried out on a limited scale, using intensive forestry techniques in the most optimal site conditions for the species. A crucial aspect of artificial forest regeneration is the use of selected seeds only in areas where stands of at least site yield classes I-II previously grew. This approach allows for the optimisation of the ratio of areas restored through natural regeneration, increases the efficiency of the selection process, ensures the

maximum preservation of the natural genetic diversity of the species, and enhances the productivity and resilience of forest ecosystems to adverse environmental factors. A priority in conserving the gene pool is to ensure optimal genetic variability in forest-forming timber species to enable adaptation to dynamic environmental conditions. Variability is also essential for the success of long-term breeding programs. In particular, it is crucial to maintain a high level of genetic diversity, which is fundamentally the determining factor in a tree's breeding value.

In most developed countries, the process of tree breeding actively uses reproductive material with pre-improved characteristics (Concept for the development..., 2019). The aim is to regenerate and conserve forest crops. A breeding population represents the concept of creating a collection of trees designed to pass on genetic improvements to subsequent generations. A breeding population is essentially a group of elite trees whose direct seed or clonal progeny are actively used to establish FSOs. These FSOs, in turn, supply seed material to specific regions. Genetic optimisation in terms of growth rate, obtained from first-generation FSOs, is achieved through modern selection technologies involving crosses between unrelated trees in these FSOs (Kang, 2020). FSOs primarily consist of clonal progeny from a select group of plus trees. Genetic diversity directly depends on the number of plus trees used. The traditional approach assumes equal representation of ramets in each clone. The variability between clones in terms of pollen and seed productivity causes an uneven contribution of clones to the overall pool of gametes in the FSOs (Donazzolo *et al.*, 2020).

Forest-forming coniferous species produce vast quantities of pollen that can be carried over significant distances by wind. Background pollination is typically viewed as a negative phenomenon, as it can reduce the effectiveness of

selective breeding (Shahini *et al.*, 2023). However, the introduction of new genes through this process can increase the genetic diversity of progeny. The main advantage of clonal forestry is expected to be significant genetic optimisation in terms of growth, achieving up to 25% for coniferous species and around 50% for deciduous species (Silva *et al.*, 2020). Due to the biological characteristics of these species, it is possible to obtain approximately 50-100 rooted cuttings from a single donor plant (Cobo-Simón *et al.*, 2020). Consequently, commercial clonal propagation systems require a continuous influx of new donor plants to maintain optimal levels of genetic diversity in clonal orchards.

The most effective approach to population-based selection involves ensuring a balance between productivity and species diversity during forest regeneration. The primary challenge lies in the fact that the most productive stands often lack sufficient genetic variability, while genetically polymorphic populations frequently exhibit low forestry value and productivity. In this context, the most successful approach is to select within population formations that exhibit a balanced combination of diversity, productivity, and resilience. To address this challenge, the following fundamental approaches are employed:

- ◆ a “non-random” sampling system based on the principle of “best stands and trees from the best”;

- ◆ comprehensive analysis of variability and productivity at various hierarchical levels (population, individual, gene, chromosome);

- ◆ index (rating) system for data summarisation and comparison of stands based on various indicators;

- ◆ a balanced combination of diversity, productivity, and resilience.

Forestry breeding methods aimed at preserving genetic diversity should facilitate a balance between productivity and sustainability.

The proposed concept involves a systematic approach that allows for the identification of stands within specific populations that are of the highest value from both a forestry and genetic perspective. The concept involves the use of vegetative propagation techniques, and the process of reproducing forest ecosystems using improved seed material and clones in artificial orchards. Special attention is given to maintaining valuable genetic material *ex situ* within forest seed production facilities, including FSOs, trial cultures, and clone archives of plus trees. Additionally, the feasibility of creating interpopulation hybrid seed orchards should be emphasised.

Genetic diversity is the foundation of biological stability; it enables species to adapt to changing conditions, including the impacts of climate change and emerging diseases. It is the foundation for current and future breeding programs and the development of new cultivars. In addition to their invaluable contribution to ecological sustainability, forest genetic reserves (FGRs) provide a direct source of food for humans and animals, even during periods of poor harvests of annual crops. Inventorying, description of characteristic features, and monitoring are necessary to gain the knowledge required for a proper understanding of trends in the state of FGRs, which allows for informed decision-making in the area of sustainable management and the rational use of FGRs. *Ex situ* conservation is the most common conservation practice because most forest-forming tree species grow in the wild and are not domesticated. It also allows populations of species to continue to exist under the influence of evolutionary processes.

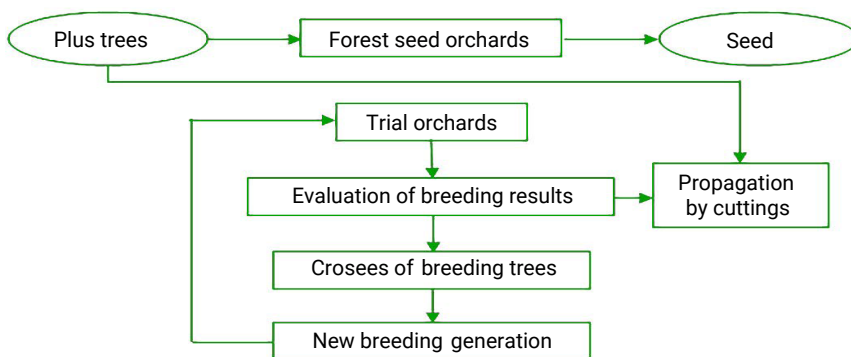
One of the promising methods for genetic improvement in forestry is intraspecific and interspecific hybridisation. An additional benefit of this method is often the heterosis effect in terms of growth rate, vigour, and even

yield (Rajora & Zinck, 2021). Furthermore, among breeding technologies, it is necessary to highlight the approach focused on new sets of genetic traits, differentiation of hybrid generations based on wood quality, disease resistance, and adaptability to adverse weather conditions. Quite often, hybridisation of suitable species creates optimal conditions for the mass production of high-yielding and fast-growing hybrids, which can be actively used in forest management systems. The optimal method for creating new hybrid tree varieties is the synergy of artificial hybridisation and subsequent selection in later generations. Interpopulation hybridisation to preserve and develop the gene pool and species diversity is implemented through the method of genotype convergence, which ensures the artificial restoration of gene combinations (Ahmar *et al.*, 2021).

To effectively preserve genetic potential in forestry, it is advisable to use biotechnological procedures involving the mass propagation of timber plants. The development of vegetative propagation procedures aimed at mass replication of valuable genetic traits in progeny allows for an intensification of breeding efficiency. The testing of vegetative propagation methods demonstrates a significant reduction in costs, contributes to an increase in the volume of

planting material, and intensifies the propagation of valuable hybrids, forms, and cultivars, the original material of which is often represented by single specimens. A priority principle in the forest breeding practices of developed countries, such as Sweden, which has demonstrated the highest efficiency, is the implementation of individualised breeding programs for the optimisation and conservation of the gene pool of each forest-forming species. A differentiated strategy has several advantages, including the consideration of differences between timber species, natural climatic and site conditions, and the population structure of each species. The proposed concept defines a promising task for the development of breeding programs by research and forestry organisations in Kyrgyzstan.

A thorough review of the state of forest breeding programs in Sweden at the beginning of the 1990s was conducted by Ö. Danell (1991). The researcher proposes an algorithm for a long-term breeding strategy in forestry that has demonstrated significant effectiveness. The initial source of selection-improved reproductive material of known origin is plus trees selected from natural stands. Forest seed orchards were established from cuttings taken from these trees (Fig. 2).



**Figure 2.** Forest selection scheme in Sweden

**Source:** M. Nonić & M. Šijačić-Nikolić (2021)

Concurrently, a significant number of experimental orchards were established in Sweden, including about 1000 trial plots across the country. As shown in Figure 2, the breeding work began with the selection of plus trees, from which first-generation forest seed orchards were created. Simultaneously, test orchards were established from seeds of plus trees. After evaluation of the testing, cuttings from the best trees were used to create second-generation FSOs. Crosses were made between trees to obtain a new generation, which also underwent field testing. Seeds and vegetative material were obtained from the best variants. By the early 1990s, Sweden had selected the following numbers of plus trees and promising clones for four main species: *Pinus sylvestris* – 6800 plus trees; *Picea abies* – 5600 plus trees + ~13000 clones; *Pinus contorta* – 200 plus trees + 1200 families; *Betula* spp. – 1450 plus trees (Danell, 1991). In each seed zone of Sweden, 600 plus trees of a particular species were tested. As a result of the testing, the 50 best plus trees were selected and used for further breeding and the creation of the next generation of FSOs.

As demonstrated by Sweden's successful experience, the optimal management of forest use and regeneration of forest ecosystems requires the development of breeding programs, both for individual forest timber plants and for their communities. Such programs should include:

- ◆ development of an ideal variety or selectively improved material;
- ◆ selecting existing or developing new breeding methods;
- ◆ studying, collecting, and preserving the original material for breeding;
- ◆ obtaining varietal or selectively improved material for regional needs and creating specialised orchards for various purposes;
- ◆ field trials;
- ◆ variety testing and zoning of the most valuable selections;

◆ using promising propagation methods and other provisions that take into account the characteristics of the forest timber species used, the natural and economic conditions of the regions, and their development prospects.

Implementing environmental innovations in forest breeding practices will ensure the long-term measurement of competitiveness and the formation of a climate-safe operating environment for forest enterprises. Typically, the process of innovation is aimed at preventing and mitigating environmental impacts while simultaneously maximising profits. A priority vector for optimising the forest management system is the formation of vertically integrated associations of environmentally oriented economic entities, which should potentially include producers of ecological raw materials, final products, and providers of energy-efficient, resource-saving, and environmentally safe selection technologies. Particular attention should be paid to establishing an effective system for monitoring and evaluating the efficiency of implemented technologies and measures within the framework of the innovative environmental development concept.

## Discussion

Most contemporary scientists whose research focus is on forest breeding technologies, which could ensure progress towards the preservation of genetically sustainable populations, confirm the extremely negative impact of depleting traditional forestry practices on the environment, especially given the intense negative dynamics of the climate.

For example, scientists H. Rachmat *et al.* (2020) argue that modernising forestry involves a phased transition from traditional to high-tech production while implementing principles of sustainable development. Through this research, scientists have proven that a nursery is a way to conserve species by

collecting seedlings. In this study, many seedlings were collected to support the conservation and management of genetic resources of certain species. More than 60% of the collected species were endangered and were conserved *ex situ* and maintained in good condition through the nursery. The scientists propose developing the nursery as a place to collect a variety of species, which would save space and allow for the collection of more individuals. The researchers' development is of practical interest to Kyrgyzstan and is foreseen as an effective methodological approach for organising breeding work.

Most contemporary scientists, particularly N. Isabel *et al.* (2020), position breeding technologies in forestry as the foundation for preserving genetic diversity. These technologies are synergistic with decarbonisation technologies and sustainable development priorities, ensuring the regeneration of the resource potential of the forestry sector amidst the shift towards a circular, renewable, and sustainable economy. The precise phenotyping proposed by the scientists opens up new avenues of research that can help address specific issues, such as resistance to biotic and abiotic stress. To minimise redundant storage, optimise data queries, and keep pace with technological advancements, the authors advocate for the significant benefits of developing cyberinfrastructures that support all aspects of the data lifecycle, from acquisition to storage, integration, and visualisation. The researchers' findings suggest that the level of eco-modernisation in forestry approaches serves as an indicator of the effectiveness of applying scientific research and development. At the same time, one could argue with the scientists about the ease of implementing cyberinfrastructures. Their implementation and support require significant improvements in practices in the areas of data standardisation, ontology, analytics, and integrated databases.

Continuing this line of thought, the differentiated approach to breeding optimisation and gene pool conservation programs for each tree species, proposed as a priority in the current research, receives positive reviews in the studies of contemporary scientists. For example, D. O'Brien *et al.* (2022) are convinced that the number of clones in the selection process does not serve as a characteristic of the gene pool if there are differences in the number of ramets within clones and their seed productivity. The researchers propose a statistical model to determine the optimal number of clones in FSOs for several coniferous species. Moreover, the model considers the influence of key conditions, particularly fertility and background pollination. At the same time, scientists N. Dinato *et al.* (2020), and S. Aitken (2021) argue in favour of the expediency of individualising breeding programs in forestry to achieve maximum efficiency.

Recent studies by H. Gaisberger *et al.* (2020) and M. Vivas *et al.* (2020) demonstrate a smaller time gap between selection and implementation of results in the case of vegetative propagation, compared to the process of establishing FSOs and producing seed material. Researchers argue that the proposed method produces a limited number of clones, and the resulting timber exhibits greater uniformity.

At the same time, Y. Yin *et al.* (2021) draw attention to the fact that monoculture orchards possess the effect of maximum genetic optimisation, simultaneously increasing the risk of losing genetic diversity. Transgenic technology is increasingly used in forest tree breeding to overcome the shortcomings of traditional breeding methods, such as a long breeding cycle, complex cultivation environment, and complex procedures. According to the authors, through the introduction of exogenous DNA, genes tightly related or contributed to ideal traits, including resistance

to insects, diseases, and herbicides, have been transferred to various forest trees. It is worth disagreeing with the conclusions of the scientists regarding the potentially low efficiency of transformation. It may hinder the cultivation of genetically modified trees and the identification of molecular-genetic mechanisms in forest trees compared to annual herbaceous plants (Yanitskyi, 2024).

Forest geneticists B. Vinceti *et al.* (2020) developed a multiple-population selection system that allows for the synergy of conserving the gene pool of timber species with intensive long-term selection. A survey conducted by the researchers demonstrated a positive attitude among respondents towards the use of forest reproductive material that is foreign to the planting site to better match predicted future climatic conditions, by introducing either a new local tree species or a new non-local genotype of an already planted species (while maintaining the same). At the same time, in the context of Kyrgyzstan, forest management authorities will require more evidence of the potential benefits of active adaptation and management to mitigate the impacts of climate change. Financial incentives at the state level are expected to be effective in achieving these goals.

In many contemporary scientific research, particularly those of J. Amaral *et al.* (2020) and S. Singer *et al.* (2021), the concept of somatic embryogenesis is being developed. The authors argue that it is possible to obtain a virtually unlimited number of genetic copies from embryogenic cell lines using this method. The scientists consider the supposed "risks" in the context of plant breeding as a whole, comparing the frequencies of spontaneous mutations with those (both expected and unpredictable) that occur through various conventional and biotechnological approaches to breeding, including transgenesis and genome editing. It is necessary to suggest, in

addition to the scientists' conclusions, that global regulatory asynchrony surrounding genetically modified crops should be taken into account, which would allow for a more complete anticipation of associated risks.

Research into somatic embryogenesis forms the foundation of a strategy for family forest management with vegetative propagation, where seeds for somatic embryogenesis are obtained from controlled crosses of plus trees. In a review article by D. Borthakur *et al.* (2022), the potential risks of undesirable disruptions were demonstrated in some cases, while at the same time emphasising the absence of deviations in the phenotype and growth of plants. Overall, the proposals of scientists in the concept of modern breeding measures in forestry for the conservation of genetic diversity indicate the promise of the concept proposed in the current study. At the same time, maintaining the genetic heterogeneity of Kyrgyzstan's forests requires the use of breeding and genetic methods based on a population approach.

In the research of E. Enfissi *et al.* (2021), it is noted that the primary task of developing breeding technologies in forestry is to form stable forest ecosystems that can mitigate the negative impacts of climate change and the risks of biodiversity loss. The scientist analyses the component-functional structure of a typical algorithm for environmentally safe forest management, noting the expediency of using the technological potential of innovative breeding strategies and updating the need for intensive industry investment. It is difficult to disagree with the author. It should be added that the concept of renewability is now seen as a key element of sustainable forest complexes, ensuring an adequate level of regeneration of natural environment components, which can function effectively without requiring significant financial subsidies. Numerous scientific studies demonstrate

that timber species breeding programs, when correctly planned and implemented, do not lead to a narrowing of genetic diversity. On the contrary, modern forestry breeding methodology encompasses the genetic variability within a given area, transmitting it through improved seeds and clones into artificial orchards during forest regeneration, thereby contributing to the preservation of the best gene pool. Most scientists emphasise the potential of assimilating clone archives of plus trees and trial crops in forestry. Researchers argue that they all contain valuable genetic material – *ex situ* – which is the basis for the conservation of genetic diversity.

### Conclusions

The conclusions drawn from the research convincingly demonstrate that the state of the gene pool in Kyrgyzstan's forest ecosystems is shaped by the optimisation of the selection policy in the industry. The breeding modernisation of Kyrgyzstan's forestry should focus on the gradual replacement of extensive forest management methods with intensive ones based on the principles of sustainable development. Priorities for the sustainable development of forest ecosystems include sound strategic planning for the innovative and technological development of the forestry industry, as well as a system of effective regeneration and preventive measures. The preservation of genetic variability is, in this case, a necessary condition for adaptation to the dynamics of exogenous conditions and successful selection.

In Kyrgyzstan, it is deemed appropriate to apply the successful practical experience of other countries, which will provide the basis for addressing the current issues of identifying reserves for preserving genetic diversity. The practical experience of Sweden in the context

of seven alternative forest timber breeding programmes could be partially applied in the Kyrgyz context. Analysis of the impact of modern tree breeding activities on the dynamics of genetic diversity shows that FSOs are the optimal source of improved seeds for forest regeneration. The study paid particular attention to the potential of background pollination in FSOs, considering the dual concept of both reducing the selection effect and simultaneously increasing the level of genetic variability in the progeny. At the same time, it was established that clonal selection – the foundation of clonal forestry – contributes to a narrowing of genetic diversity. If modern scientific recommendations are followed, the reduction of genetic diversity can be minimised. The use of the family forest management concept, which is based on vegetative propagation, significantly intensifies the level of genetic variability in the progeny. An approach based on the selection of multiple populations creates optimal preconditions for combining intensive long-term selection and maximum preservation of the gene pool of timber species.

The development and integration of innovative monitoring and forecasting systems as a primary resource for intensifying the effectiveness of breeding technologies in forestry is a priority area for future research. Of particular importance is the integration of successful international experience, and the development and implementation of innovative breeding methods based on the principles of sustainable development.

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### Conflict of Interest

None.

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## **Сучасні методи селекції в лісівництві, спрямовані на збереження генетичної різноманітності**

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**Анотація.** Дослідження присвячено аналізу впливу сучасних селекційних заходів у лісівництві на рівень генетичної різноманітності лісових деревних порід. Виявлено, що основним джерелом поліпшеного насінневого матеріалу для генетичного відтворення лісів є базові лісонасінневі плантації. Детально проаналізовано аспекти впливу на показники генетичної варіативності нащадків визначальних чинників – фонового запилення та числа клонів. Вивчено потенціал фонового запилення на лісонасінневих плантаціях у контексті суттєвого зниження ефективності селекційних заходів та паралельного підвищення рівня генетичної варіативності потомства. Проведено аналітику даних мінімальної кількості клонів на лісонасінневих плантаціях на підставі практичного досвіду розвинених інших країн. Досліджено динаміку варіативності клонів в аспекті фертильності. Визначено можливість впливу клонового добору на генетичну різноманітність деревних порід у напрямку зменшення. Підтверджено, що інтеграція концепції сімейного лісівництва, яка передбачає використання технологій вегетативного розмноження, у селекційну стратегію значно збільшує рівень генетичної варіативності нащадків. Доведено, що система селекції множинних популяцій є основою забезпечення оптимальних попередніх умов для синергізації процесу довготривалої інтенсивної селекції та збереження генофонду деревних

порід. Визначено відсутність негативного впливу на генетичну різноманітність реалізації комплексу оптимально спланованих селекційних програм. Водночас, встановлено потенціал інтенсифікації якості збереження генофонду в процесі відтворення лісових екосистем за допомогою поліпшеного насінневого матеріалу та клонів у штучних насадженнях. Особливу увагу приділено утриманню *ex situ* – цінного генетичного матеріалу в об'єктах лісового насінництва, в тому числі, лісонасінневих плантаціях, випробувальних культурах, архівах клонів плюсових дерев. У процесі дослідження доведено, що імплементація сучасних інноваційних рішень і наукових рекомендацій дає змогу звести до мінімуму процеси зменшення генетичного різноманіття лісових порід. Результати можуть знайти практичне застосування в сучасних селекційних програмах у лісівництві

**Ключові слова:** клонова технологія; соматичний ембріогенез; фонове запилення; *ex situ*; кількість клонів