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ADVANCEMENTS IN MECHANIZED TREE PLANTING: ENHANCING EFFICIENCY AND SUSTAINABILITY IN FORESTRY

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Abstract: Tree planting is a labor–intensive process in forestry, often carried out manually or with semi–automated planters. With the increasing demand for wood and the need for sustainable forestry practices, mechanized planting solutions are becoming essential. This study analyzes existing planting technologies, highlighting the benefits of automation in reducing labor costs and improving efficiency. The research classifies seedlings based on root type—bare–root and containerized—and explores different planting techniques, such as pit and slit planting. Mechanized solutions, including augers and specialized planting devices, enhance productivity, particularly for containerized seedlings, which exhibit higher survival rates due to reduced transplant shock. Results indicate that mechanization significantly increases planting efficiency and ensures better regeneration success. The findings support the adoption of automated planting systems to address labor shortages and improve forestry sustainability.
Keywords: mechanized planting, sustainable forestry, reforestation

1. INTRODUCTION

Agrotechnological procedures related to forest management, including planting, are burdensome and the energy expenditure of the people working is very high. Nowadays, planting is usually carried out manually, and sometimes with the use of planters coupled to universal tractors [1].

The problems and challenges of modern agriculture [2] can be largely identified as present also in forestry [3,4]. The most important one is the necessity to meet the needs of the Earth's growing population for wood, used to produce consumer goods, such as paper, furniture, construction materials, etc. Further needs are related to the necessity to introduce principles of sustainable forest production that will ensure the safety of forest workers, support environmental balance and guarantee the above–mentioned sufficient level of productivity [5]. The implementation of these principles is best achieved by introducing automatic machines in forestry production [6], especially for those tasks that require manual labor—including planting, which is characterized by a high energy input [7,8,9]. These solutions will also reduce many other problems of modern forestry: low unemployment and, therefore, a limited number of workers available on the market (especially in the case of monotonous and tedious seasonal tasks, performed in the open terrain, often in unfavorable weather conditions (heat waves and rain)). These factors result in a reluctance to take on this type of work [10,11].

Based on the analysis of devices and machines used for tree planting [12,13,14], it can be concluded that what are mostly used for this purpose are simple manual devices and classic planters attached to agricultural tractors that need human operators. There are also a few machines that offer a certain range of planting automation, especially in the aspect of planting forest tree seedlings with a covered root system. However, these are devices that still require a significant amount of manual operation [15,16,17,18]. This work involves manually transferring seedlings from containers to appropriate storage units, from which the seedlings are next collected by automatic systems that then plant them into the soil. These structures are modelled on existing solutions for vegetable planters—cabbage, celery, lettuce, etc. [19,20,21]—this is due to the fact that the seedlings of these vegetables are similar to tree seedlings.

Seedling transplanting is a method of efficiently transplanting seedlings from the nursery to the planting site. Transplanting can increase the spacing and row spacing between seedlings, expand

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their survival space, and cut off their main and larger lateral roots during the transplanting process. Consequently, a large number of horizontal roots and fibrous roots can be produced from the broken root section, thus improving the survival rate of seedlings [22,23,24].
Mechanized tree planting has been shown to be time efficient [25], so the machines can potentially alleviate future labor shortages. In addition, because planting trees mechanically with today's machines produces high–quality regeneration (often with better quality than when trees are planted manually [26,27,28]), foresters are keen on this option, rather than the standard option of manual planting [29,30,31].
Traditional tree planting methods primarily rely on manual labor or semi–automated systems, where workers use handheld tools or tractor–mounted planters. These methods, while effective, have limitations such as high labor costs, slow planting rates, and increased worker fatigue. Additionally, manual planting is highly dependent on worker availability, which has become a growing concern due to labor shortages.
In contrast, emerging mechanized solutions aim to address these limitations by integrating automation, robotics, and AI–driven systems. Modern mechanized planters are being designed with GPS–guided precision planting, automated seedling loading, and real–time soil condition monitoring. These advancements not only reduce the need for human intervention but also enhance planting accuracy, optimize seedling survival rates, and minimize soil disturbance. Furthermore, future planting technologies may incorporate drones and autonomous ground vehicles capable of mapping terrain and identifying the most suitable planting locations with minimal human supervision.
The shift from manual and semi–automated planting to fully mechanized and intelligent systems represents a significant step toward improving efficiency and sustainability in forestry. By reducing dependence on human labor and increasing the precision of planting operations, these technologies will play a crucial role in ensuring the long–term health and productivity of forest ecosystems.

2. MATERIALS AND METHODS

Planting is the operation of artificially installing forest species, which involves the use of seedlings as reforestation material. It is the most commonly used reforestation method in our country.
Depending on the way the roots are presented, the seedlings can be classified as follows: seedlings with bare roots and seedlings with protected roots. They can be planted in two ways: in holes or in slits.
This procedure is the most commonly used and can be applied even on soil–less land if borrowed soil is used. The procedure allows for the planting of all categories of seedlings, whether small or large, with bare or protected roots, etc.


Figure 1 – Motor auger for drilling holes [32]


Figure 2 – Tractor–powered auger for drilling holes [33]

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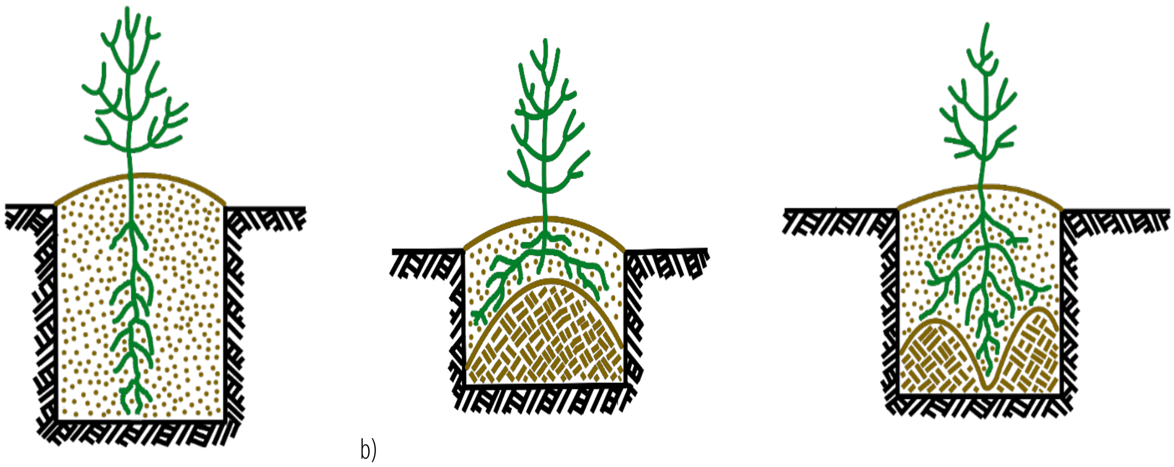
The planting holes are prismatic or cylindrical in shape and have dimensions correlated with the size and shape of the seedling's root system. In the case of heavier, compacted, or poorly prepared soils, it is recommended to create oversized holes to provide the seedling with a sufficiently large volume of loose soil, allowing for the unhindered development of the roots in the first years after planting. For mechanized hole creation, the following tools can be used: the motor auger (Figure 1) and the tractor–powered auger (Figure 2).

Motor drills can also be used on steep terrain, where mechanized soil preparation is not possible. For flat terrain, tractor–mounted and tractor–powered augers can be used, allowing for the drilling of 50 to 150 holes per hour, with diameters ranging from 40 to 120 cm.

In order to better position the roots and prevent their bending or twisting (Figure 3), for seedlings with a taproot system, a deeper excavation can be made at the bottom of the hole. For seedlings with a spreading root system, a small mound can be created to spread the roots, while for those with a combined taproot and spreading root system, a mound with a slit in the central part can be made.

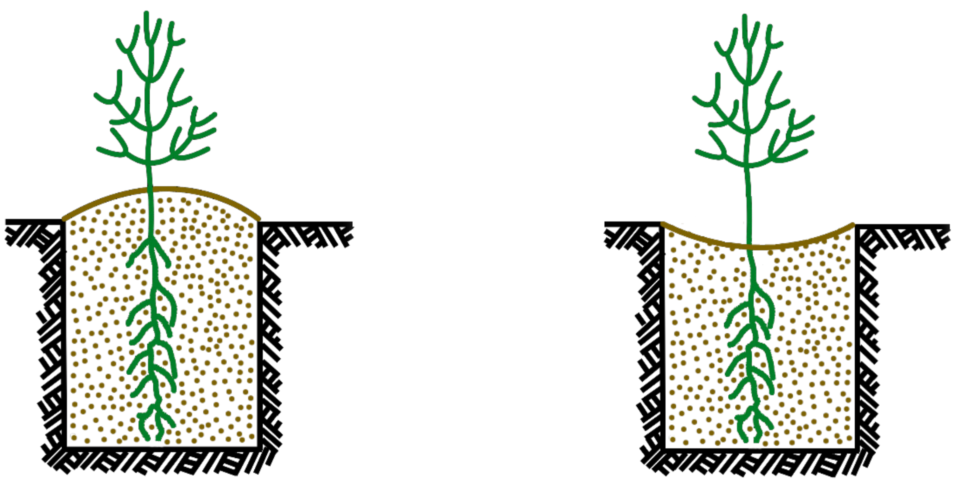


a) b) c)

Figure 3 – Variants of planting in holes in relation to the shape of the root system [34]
a) pivoting root; b) spreading root; c) pivoting–spreading root

On soils with excess moisture, to drain the excess water from current rainfall, the soil is gathered after planting and compacted around the base of the stem in a convex shape (Figure 4a). In arid areas, a slight concavity is created around the seedling to retain water from rainfall and direct it to the roots (Figure 4b).

Planting in a slit for bare–root seedlings involves inserting the seedling's roots into a slit opened in the soil with various tools. It is a simple and expedient procedure.



a) b)

Figure 4 – The method of arranging the soil after planting [34] a) convex shape, b) concave shape

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By gathering and pressing the soil to close the slit, the seedling's roots are arranged differently than their normal position in the nursery. They are laid out in a single plane, in a fan shape, which is why the planting in a slit procedure is applied to small, young seedlings (1–2 years old), with a pivoting–trailing root system and a well–proportioned root structure. For successful planting, the soil must be free of weeds, moist, and loose.

Due to its drawbacks, particularly related to the way the root system is positioned in the slit made in the soil, the planting in a slit procedure is rarely practiced in our country.

For manual planting in a slit, the most commonly used tools are the planter, the forestry hoe (Figure 5), and the mattock (Figure 6).

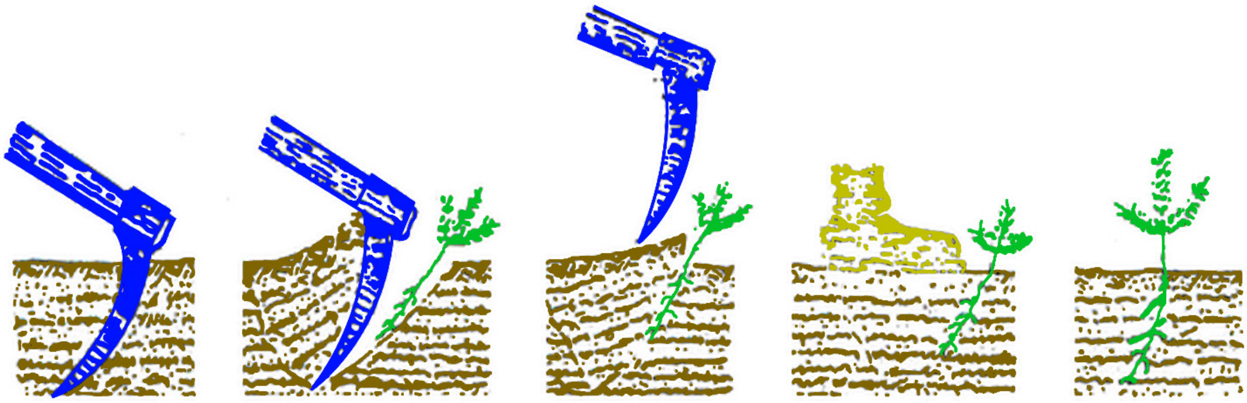

Figure 5 – The planting scheme with a forestry hoe [34]

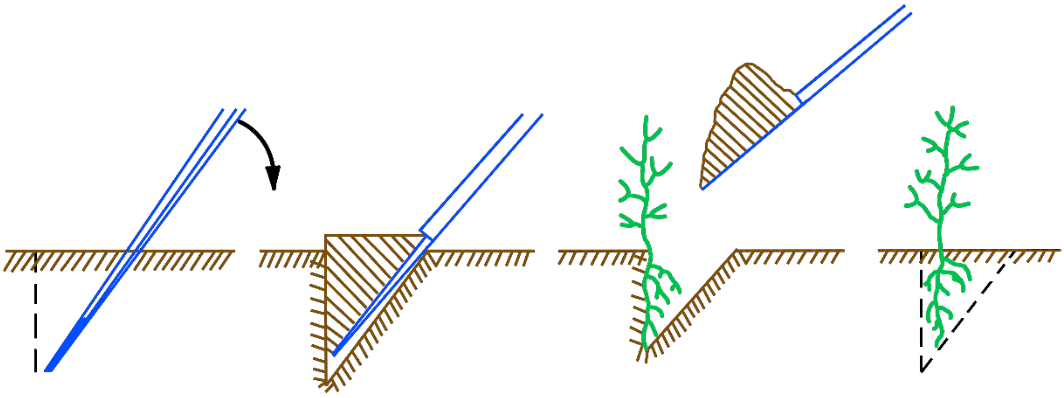

Figure 6 – The planting scheme with a spade [34]

Seedlings with protected roots are the most recommended for afforestation on land with difficult vegetation conditions. They are more expensive than those with bare roots, but during the planting process, the roots remain in their natural position and are undisturbed in their connection to the soil or the physical environment in which they grew. Another advantage is their easy and rapid adaptation to the new living conditions.

In general, planting holes are equivalent in shape and size to the soil ball or container in which the roots are found.

The planting of bare–root seedlings is carried out in spring, before bud break, or in autumn after the lignification of annual shoots. Seedlings can also be planted during winter, but only during thawing periods when temperatures continuously remain above 5°C throughout the planting period.

Seedlings with protected roots can be planted in spring, even after they have entered vegetative growth, although there is still a risk of loss due to drying out.

In our country, at least in the hilly and mountainous areas, the most favorable season for carrying out plantings is early spring, immediately after the snow melts, the soil thaws, and it dries out (during the “snow melt period”), when the seedlings benefit from enough moisture in the soil and atmosphere, as well as the absence of excessively high temperatures [34].

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3. RECENT INNOVATIONS IN MACHINERY AND TECHNOLOGIES

In addition to the previously mentioned motorized and tractor–mounted augers, a series of recent technological innovations allow for much faster and more efficient planting. The use of precision GPS systems in tree planting has become an increasingly widespread practice, allowing for stricter control over the planting location and the depth at which the roots are placed, thus optimizing the success of forest regeneration. These systems can also manage real–time data on soil moisture and type, significantly improving seedling survival rates.

Another example of innovation is automated planters, which can load and plant seedlings in a single motion, reducing the time and effort required compared to traditional methods. These machines can handle different types of roots, including those with protective systems, and can be adjusted to adapt to various soil conditions.

4. ADVANTAGES OF MECHANIZED PLANTING

Mechanizing the planting process offers a number of significant advantages in reforestation efforts. First, the reduction in labor costs is evident, as machines can plant a much higher number of seedlings in a short amount of time. These machines can also plant in difficult conditions, such as rough or wet terrain, where manual planting would be impossible or would require much more time and effort.

Furthermore, mechanization helps reduce planting errors and improves the uniformity of seedling distribution. Machines are designed to place seedlings at the optimal depth and spacing, contributing to the healthy development of trees. Modern technologies also help minimize environmental impact by reducing soil compaction and disrupting local ecosystems.

5. REPLACING MANUAL PLANTING

Although manual planting will remain an essential practice in certain harder–to–reach areas, mechanized planting technologies are increasingly capable of completely replacing traditional methods in many areas. In addition to the savings in time and resources, the use of automated planters can lead to higher planting success rates, especially under climate change conditions, where the rapid adaptability of technologies becomes crucial.

6. RESULTS

Planting seedlings with protected roots is much simpler and more productive than planting seedlings with bare roots. For planting containerized conifer seedlings, the Pottiputki planter (pipe type) (Figure 7) is used, with the planting team's productivity ranging from 1,300 to 1,500 seedlings per day [35].

Figure 7 – Containerized seedling planting device Pottiputki (pipe type) [35]

In the case of containerized deciduous seedlings, they are planted in a split trench using a forest spade, with a planting team productivity of 700–900 seedlings per day.

A clear advantage of containerized seedlings is that the success of regeneration is significantly higher compared to plantations established with bare–root seedlings. The fact that they have protected roots and do not suffer from water stress after planting is an important factor. The planting period is significantly extended from March to May, and autumn plantings also become favorable.

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DAMCON has been offering a wide range of mechanization for the tree nursery for more than 50 years. This company manufactures the PL–10 forestry seedling planter (Figure 8). The tree planting machine PL–10, the smallest tree planting machine in the Damcon range, is extremely suitable for planting rootstocks, whips and conifers, among other things.


Figure 8 – PL–10 forestry seedling planter [36]

The PL–10 is available as a 1–row machine, but also as a 2–row, 3–row or even 4–row machine. These tree planting machines can be equipped with a planting element of 5, 10, 15, 20, 25 and 30 cm wide. The 1–row machine has a planting capacity of 4,000–5,000 plants per day, the 4–row machine goes from 16,000 to 20,000 plants per day.

These tree planting machines can also be equipped with a GPS plant distance marker or Block plant distance meter. The GPS marker is controlled by the GPS system from the tractor.

The tree planting machines of each type have various options. In addition, specials are also possible. The tree planting machines simplify and facilitate the planting of trees and shrubs [36].

The SDK model (Figure 9), produced by the company Wiesław Królik, is another tree planting machine equipped with a heavy–duty plow, large baskets for trees, a telescopic lateral marker for marking the next row (which can be mounted on either the right or left side of the machine) – up to 4 meters, and a marker for planting distances.


Figure 9 – Tree planting machine model SDK [37]

The SDK tree planting machine is an innovative piece of equipment designed to optimize and automate the process of planting trees and shrubs. The machine plays a significant role in reducing time, saving human resources, and increasing productivity in planting activities over large areas.

Technical data of the SDK tree planting machine:

- Transport dimensions (with raised baskets) Length x Width x Height – 1900mm x 1180mm x 1440mm
- Working dimensions (with lowered baskets) Length x Width x Height – 1900mm x 2700mm x 1100mm
- Plow width – 25 cm
- Planting depth – up to 40 cm
- Efficiency – up to 300 trees/hour
- Power requirement – 48 kW
- Weight – 250 kg

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Advantages of the SDK tree planting machine:

- Significant cost reduction as a large part of the required labor force is eliminated.
- Trees are planted uniformly, with precise distances between trees and rows. This greatly improves cultivation efficiency.
- Durability of the machine – the tree planting machine is made from very high–quality materials, ensuring long–term use.
- Increased productivity – the tree planting machine is ideal for various reforestation projects or establishing large–scale orchards.

One of the most important features of the SDK tree planting machine is the planting precision and the low power requirement for the tractor. The thin plow and the three blades located at the front of the planting machine help maintain the equipment on a straight line, even with low–power tractors. The wheels of the machine perform two tasks simultaneously – they push and compact the soil. By correctly choosing the wheel tilt angle, the machine operator no longer needs to make time–consuming adjustments [37].

Dutch firm Basrijs develops and manufactures professional machinery for horticulture and arboriculture. They have created the BPS\PEPE70 disk planter (Figure 10), intended for planting fruit and vegetable crops and young trees.

The operating procedure is as follows: the furrow opener makes an appropriate. Plant is inserted by hand at a mark between the plant discs. The plant discs insert the plant into the furrow and release the plant into the furrow. The furrow is firmly pressed by the pressing wheels. General specifications are given in Table 1.

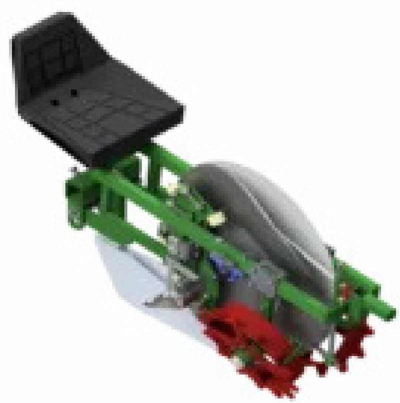

Figure 10 – Disc planter BPS\PE70 [38]

Table 1 [36]

Diameter of the plant discs	700 mm
Maximum plant height above the ground	35 cm
Minimum row distance for single frame	22.5 cm
Minimum row distance for tandem frame	45 cm
Planting depth	5–15 cm
Plant spacing in the row	from 5 cm
Capacity	1000–2000 plants per person per hour

Optional equipment: various furrow openers, furrow scrapers, plant holders, plant rack(s), crate rack(s), support wheels, track markers, coulter discs, slotted discs, rippers, electric plant distance control, canopy.

7. DISCUSSION

Forest seedling planting represents a crucial stage in forest regeneration, and the efficiency of this process is influenced by factors such as the type of seedlings, the techniques used, and the degree of mechanization of the task. The study's results highlight that the use of mechanized technologies in planting significantly increases productivity and seedling survival rates, providing a viable solution to the current challenges in forestry.

Efficiency of planting methods

Manual planting, while still the predominant traditional method, involves a high consumption of energy and time. On the other hand, mechanizing the planting process by using augers to drill holes and automated planting devices significantly reduces physical effort and the time required for each stage of the process. As a result, the overall efficiency of the operation is increased, and the impact on human resources is reduced.

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The type of planting material also influences the outcomes. Seedlings with protected roots have shown a higher survival rate compared to those with bare roots, due to the protection provided by the soil ball, which reduces transplant stress. Additionally, using the Pottiputki device for planting containerized conifer seedlings allows productivity levels of up to 1,500 seedlings per day, far exceeding the capacity of a team planting manually.

Impact of mechanization on forest regeneration

The adoption of mechanized technologies not only optimizes the planting process but also ensures a more uniform distribution of seedlings, better soil compaction, and optimal positioning of the root system. These aspects contribute to the harmonious development of seedlings and better adaptation to environmental conditions.

Another advantage of mechanization is its ability to plant on difficult terrain, such as steep slopes or compacted soils. The use of a motorized auger is an effective solution for such terrains, allowing for the planting of a significant number of seedlings in a short period of time. However, to ensure maximum success, it is essential that the soil is properly prepared in advance.

Sustainability aspects

Mechanized planting aligns with sustainable development goals by reducing reliance on seasonal labor, minimizing the physical effort of forestry workers, and increasing the efficiency of forest regeneration. Additionally, mechanization reduces risks associated with manual labor, such as workplace accidents or exposure to unfavorable weather conditions.

However, the large–scale implementation of automated technologies requires significant initial investments and proper staff training. In the long term, the economic and ecological benefits of mechanization outweigh the initial costs, contributing to more efficient and sustainable management of forest resources.

Adoption of planting technologies in the context of climate change

As climate change continues to affect weather patterns, periods of drought and extreme precipitation are becoming more frequent. Mechanizing the planting process can help adapt to these conditions by enabling quick and precise planting of seedlings in unpredictable weather. Advanced planting technologies also allow for the selection of seedlings that are more resistant to harsh climatic conditions, thus reducing the risks for long–term forest regeneration.

Relationship between mechanization efficiency and environmental protection

Mechanized planting not only improves efficiency but also contributes to environmental protection. The use of modern equipment reduces the ecological impact by minimizing carbon emissions and reducing the use of fossil fuels compared to traditional planting methods that rely on manual labor or less efficient equipment. Additionally, mechanized machines can be equipped with technologies that reduce soil compaction and minimize damage to local ecosystems.

Social impact of mechanization

Mechanization of planting may significantly reduce the need for manual labor, which can affect workers from rural communities dependent on this type of work. It is important to develop strategies for transitioning these workers into other forestry–related activities or offering retraining opportunities. Additionally, the increased efficiency in planting could lead to more reforestation projects, creating new jobs in other related fields (e.g., research, forest management, biodiversity protection).

Emerging technological innovations

As technology advances, new innovations may arise that can enhance the efficiency and sustainability of mechanized planting. For example, the use of drones to monitor soil conditions and planting progress, or the development of planting techniques using artificial intelligence (AI) that can identify the best planting areas based on detailed ecological data analysis. These

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technologies could optimize not only the planting process but also long–term forest management, helping protect and improve forest ecosystems.

Challenges and limitations of mechanization in mountainous or inaccessible areas

Despite the many advantages, mechanized planting may face significant challenges in mountainous or inaccessible areas. While motorized augers and other specialized equipment are effective, very steep terrains, rocks, or dense vegetation can limit the accessibility and efficiency of mechanized equipment. In these cases, a combination of mechanized and manual methods could be the ideal solution to ensure the success of reforestation projects in difficult regions.

Post–planting monitoring and data usage

After planting the seedlings, continuous monitoring of their condition is crucial to identify potential problems such as water shortages, pest attacks, or planting errors. Modern technologies for monitoring vegetation and soil health, including moisture sensors and drones for land surveillance, could significantly improve post–planting management, ensuring higher success rates in forest regeneration.

Initial costs vs. long–term benefits

Although the initial costs of acquiring and implementing mechanized equipment are significant, indirectly, investments in planting technologies can reduce long–term expenses by increasing seedling survival rates and reducing the need for subsequent maintenance. Additionally, the increased planting speed can lead to shorter timeframes for reforestation projects, helping improve efficiency and reduce environmental impact in a shorter time period.

5. CONCLUSIONS

The study demonstrates that mechanizing the planting of forestry seedlings is a viable solution for optimizing the forest regeneration process. The use of advanced technologies increases productivity, reduces the physical effort required, and ensures better seedling establishment. In the current context, characterized by a growing demand for wood and strict sustainability requirements, the adoption of modern planting methods is essential for the future of forestry.

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