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The aerial genesis: Seed bombing for nurturing earth and ecosystem renaissance-A review

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Abstract
Aerial seeding popularly known as "seed bombing" is an innovative approach to ecological restoration which has emerged as a game-changing tactic for overcoming the difficulties associated with large-scale vegetation recovery in a variety of landscapes. In order to achieve a thorough analysis, the methodology, ecological effects, and potential to support long-term habitat restoration is the need of the era. Seed bombs provides protection by encapsulating the seeds with suitable substrates creating a congenial microenvironment improving viability, vigor and germination. They can rapidly span extensive landscapes, even in remote and challenging terrains, enhancing the probability of successful revitalization and restoring crucial habitats through the deliberate selection of appropriate plant species. Therefore, improvements in aerial delivery technologies, such as the use of drones and specialized aircraft offer control and precision in seed dispersal, ensuring ideal seed distribution patterns and maximizing ecosystem recovery.

Keywords: Aerial seeding, encapsulation, methodology, drones, seed bombing

1. Introduction

Novel approaches are emerging as beacons of hope in a world dealing with the dire effects of climate change and global warming. Aerial seed bombing is one such solution that has caught the attention of scientists, environmentalists, and visionaries all over the world. It provides a compelling route to mitigate climate change, combat global warming, and promote environmental sustainability with ecological ingenuity. Effective strategies to combat climate change are now more important than ever as the earth's climate system experiences unheard-of changes. One particularly effective weapon in this conflict is aerial seed bombing, targeting mostly the deforested areas, degraded landscapes, and erosion-prone areas.

This technique initiates a series of transformative events by reintroducing native plant species into these desolate landscapes. As the seeds grow and take hold, they become organic allies in the struggle against the rise in greenhouse gas emissions resulting in amplified carbon sequestration. This technique involves the direct broadcasting of seeds by use of aerial means such as a drone, plane or a helicopter (Buters, 2019) [4] and is an alternative to ground-based seeding methods that include planting by hand or tractor seeding. (Barnett, 2014) [1]. It also fosters resilient habitats that support a variety of plant and animal species by restoring degraded ecosystems and increasing biodiversity. These ecosystems' preservation and restoration are in line with the Sustainable Development Goals of the United Nations, especially Goal 15 "Life on Land", which highlights the significance of safeguarding and restoring terrestrial ecosystems. It has the potential to promote social and economic advancement as well as community involvement. This method of restoration can generate employment especially in rural areas that have been severely impacted by environmental degradation. Additionally, restoring essential ecosystem services like clean air, water filtration, and soil fertility through the revitalization of degraded landscapes benefits both the health of nature and people.

Aerial seeding is best suited in circumstances where forest establishment requires minimal human assistance and over landscapes where terrain hinders conventional forest establishment methods (Lamb, 2011) [12]. The first step in this process is typically the selection of suitable seed species that are adapted to the target environment and have the potential to improve or restore the ecosystem.

The ability of the seeds to withstand regional climate, soil types, and desired ecological outcomes are frequently taken into consideration when selecting seeds. These could be native grasses, shrubs, or tree species that are suitable for the particular restoration objectives.

Depending on the size of the project and the terrain, different delivery mechanisms can be used for aerial seeding. It can involve using specialized seeding equipment on fixed-wing aircraft, helicopters, or unmanned aerial vehicles (UAVs). The timing of the seeding operation, the right seed choice, and seed treatment as well as favorable weather conditions are all necessary phenomenon for aerial seeding to be successful.

2. History of aerial seeding

The idea behind seed bombing has its origins in traditional agricultural methods. Although the precise origins of seed bombing are unclear, there are historical instances of related techniques being used by various cultures throughout the world. The traditional Japanese practice of "Nendo dango," or "earth dumplings," is an early example of seed bombing. Japanese farmers have been scattering seeds across fields and arid areas for hundreds of years. They would mix seeds with clay, compost, and other materials to form small balls. This process improved crop production and soil fertility by distributing seeds effectively and uniformly. In the 20th century, the idea of seed bombing as a reforestation strategy gained popularity.

Eventually, when the Guerilla Gardening movement first emerged in the 1970s, seed bombing became even more popular. As a non-violence method of protest and for urban greening, activists and gardeners started using seed bombs to turn vacant or abandoned spaces into thriving green spaces. The significance of civic engagement and the ability of nature to reclaim urban landscapes were emphasized by this grassroots movement.

Today, seed bombing is acknowledged as a useful tool in combating environmental issues like habitat loss, degraded landscapes, and a decline in biodiversity. It is a crucial component of ecological restoration projects all over the world due to its capacity to restore ecosystems, encourage genetic diversity, and involve local communities in conservation efforts.

3. Methodology of seed bombing

The technique of seed bombing uses a methodical approach to make sure that seeds are dispersed aerially in an efficient and effective manner, maximizing germination and seedling establishment. This innovative method transforms conventional seeding techniques and offers a scalable answer for massive ecological restoration initiatives. The procedure for seed bombing is described in the steps below:

1. **Seed selection**: Careful consideration is given to the selection of native seed species that are compatible with the target ecosystem. Various factors like plant diversity, ecological function, and local species interactions are taken into account for selecting better seed species.
2. **Seed processing**: To remove any debris, damaged seeds, or contaminants, collected seeds are cleaned, sorted, and tested for quality. Only healthy and viable seeds are used for encapsulation through this step.
3. **Seed treatment**: To improve germination rates and break seed dormancy, seeds may occasionally undergo pre-germination treatments like scarification or stratification. The likelihood of successful seedling establishment can be improved with these treatments.
4. **Seed encapsulation**: The cleaned seeds are enclosed in a barrier made of clay, compost, and possibly other organic materials. The coating protects the seeds during storage and distribution by acting as a barrier against environmental factors and providing moisture retention.
5. **Seed bomb preparation**: To increase seedling vigour and enhance soil conditions, the encapsulated seeds are combined with additional ingredients such as organic fertilizers, mycorrhizal inoculants, or water-absorbing polymers. These additives have the ability to deliver crucial nutrients and promote advantageous microbial relationships.
6. **Seed bomb drying and curing**: To ensure stability and durability, the newly formed seed bombs go through a drying and curing process in order to prevent mould or fungal growth.
7. **Seed bomb testing**: Seed bombs are frequently put through germination tests prior to full-scale deployment to determine their viability and guarantee the quality of the seeds. Before the actual aerial dispersion, this step aids in identifying any potential problems or adjustments that are required.
8. **Aerial deployment planning**: In order to determine the best areas for seed bombing, the target restoration area is carefully evaluated and mapped. Topography, vegetation cover, soil quality, and accessibility are all taken into account. The most efficient flight paths and the locations needing concentrated seed dispersal are determined during this planning phase.
9. **Aerial deployment execution**: To carry out aerial deployment, specialized aircraft, helicopters, or drones fitted with seed dispersal systems are used. Trained operators fly along predetermined flight paths and drop seed bombs at certain intervals to cover uniform targeted areas.
10. **Post-deployment monitoring and evaluation**: Following seed bombing operations, ongoing monitoring is done to gauge the emergence of seedlings, their survival rates, and the overall recovery of the vegetation. For the purpose of evaluating the efficacy of the restoration project and identifying potential areas for improvement, data collection includes tracking growth rates, species composition, and ecosystem response.

Seed encapsulation types

Seed encapsulation methods, a nexus of innovation in ecological practices, encompass a spectrum of techniques transforming seed dispersal. From clay-based shields bolstering moisture retention to biodegradable capsules fostering eco-friendliness, this introduction explores diverse encapsulation avenues revolutionizing reforestation, agriculture, and habitat restoration.

1. **Clay-based encapsulation**: This technique involves blending seeds with clay to create a protective shield that enhances moisture retention and adhesion, gradually enabling seed-soil contact for successful germination and growth.
2. **Compost-based encapsulation:** Unlike seed bombing, this approach employs compost to encase seeds, fostering nutrient-rich conditions that promote successful seed germination and early seedling growth.
3. **Biochar-based encapsulation**: Biochar-enhanced seed bombing incorporates biochar-treated seeds, utilizing its

carbon-rich composition to create a stable microenvironment for germination.

4. **Biodegradable capsules**: Utilizing biodegradable capsules for seed encapsulation involves enclosing seeds in materials like cellulose or starch that naturally degrade, promoting seed-soil contact without manual intervention and reducing the environmental footprint of seed bombing.

Fig 1: Seed encapsulation

5. **Hydrogel-based encapsulation**: This type of encapsulation coats seeds with water-absorbing polymers, ensuring continuous hydration during germination, offering vital support in arid or water-scarce settings.
6. **Coating with microbial inoculants**: Enhancing seed bombing, beneficial microbes like mycorrhizal fungi or rhizobacteria can be incorporated to boost nutrient uptake, plant growth, and overall effectiveness through seed encasement or coating with microbial inoculants.
7. **Wax-based encapsulation**: Seed coating through wax-based encapsulation involves applying melted natural waxes like beeswax, forming a protective shell that offers physical security, moisture retention, and insulation, proving beneficial in water-scarce regions.
8. **Alginate-based encapsulation**: Seed coating via alginate-based encapsulation uses brown algae-derived polymer to create gel-like capsules around seeds through cross-linking in a calcium chloride solution, offering benefits like simplified gel formation, robust adhesion, and controlled release of nutrients for improved seed viability.
9. **Gelatin-based encapsulation**: Utilizing gelatin, derived from collagen, for seed encapsulation involves forming a protective coating around seeds, enhancing hydration, protection, and adhesion, offering a biodegradable and sustainable solution for effective seed bombing.
10. **Pelletized encapsulation**: Palletization involves binding seeds with additives and binders to create pellets, offering controlled nutrient release, uniform distribution, and simplified application for effective seed dispersal in seed bombing efforts.

Elevating seed bombing: Aerial delivery mechanisms

Fixed-wing aircraft, including airplanes and drones, employ specialized containers to release seeds, ensuring precise coverage over large areas. Helicopters with adaptable platforms, are essential for areas with rough terrain, steep slopes, or thick vegetation, using seed hoppers or bags to manually drop or broadcast seeds. Balloons filled with biodegradable seed bombs or lightweight materials use gases like helium to disperse seeds from elevated altitudes. Parachutes and paragliders also provide precise seed placement by slowing descent for targeted dispersal. Pneumatic "seed guns" shoot seeds at high speeds to cover expansive regions, mounted on helicopters or drones for efficient application. These aerial systems significantly contribute to ecosystem restoration, afforestation, and revegetation efforts by tailoring methods to the target area's characteristics and coverage requirements.

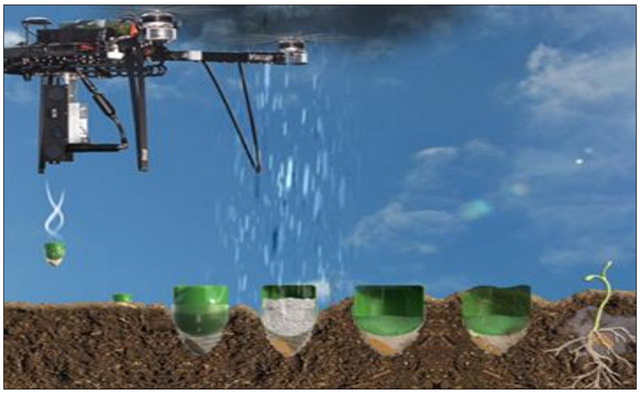

Fig 2: Seed bombing drones.

Fig 3: Seed bombing by special aircraft.

Advantages of Aerial seeding

1. **Wide coverage**: This technology is a well-established technique for sowing pastures as well as agricultural crops (Dowling *et al.* 1971) [5]. Aerial seed dispersal covers vast areas, aiding reforestation and ecosystem restoration, even in remote locations.
2. **Efficient and time-saving**: This technique can cover large areas more quickly, saving time and expenses compared to ground-based seed dispersal methods.
3. **Precise targeting**: Seeds can be dispersed in predetermined areas with high accuracy which maximizes the success of this process.
4. **Access to challenging terrain**: Aerial seed dispersal makes it possible to reach difficult terrains like steep slopes, rough terrain, or places with little ground access.
5. **Increased seedling survival:** The success of seed bombing is influenced by the ability of the seeds to germinate along with the capacity of the seedlings to establish during the first growing season. It increases the likelihood that seeds will find suitable microhabitats and environmental conditions for germination and growth by dispersing them over a larger area.
6. **Rapid ecosystem recovery**: This technique makes it possible for vegetation to grow in areas damaged by

calamities, wildfires or human-caused disturbances, hastening the return of ecological balance.

7. **Adaptability to various seed types**: This approach can accommodate a wide range of seed types, including seeds of different plant species which are compatible to that particular terrain.
8. **Reduction of soil erosion**: By encouraging the growth of vegetation on exposed or bare soil surfaces which stabilizes the soil, preventing wind- or water-induced erosion.
9. **Enhances biodiversity**: By reintroducing native plant species to degraded areas, it encourages ecological balance, provides favorable conditions for wildlife, and aids in the restoration of natural habitats.
10. **Carbon sequestration:** This method also serves as a key component in sequestering carbon dioxide from the atmosphere. By lowering the amount of greenhouse gases in the atmosphere, this helps to mitigate the effects of global warming.
11. **Climate resilience and adaptation:** By restoring ecosystems which can efficiently withstand the effects of climate change, seed bombing aids in the development of climate resilience mechanism. They contribute to the overall capacity of communities and ecosystems for adaptation by regulating local climates, maintaining water cycles, and providing natural cooling.

Challenges of aerial seed dispersal mechanism

Aerial seed dispersal technique faces multifaceted challenges that intricately influence its effectiveness. Weather emerges as a pivotal factor, where the capricious nature of strong winds, rain, and unfavorable weather patterns impairs the precision and efficiency of seed dispersal, leading to uneven distribution or potential loss. This unpredictability constrains the opportune timing for seed bombing initiatives. Vital to success is the quality and viability of seeds; meticulous handling, appropriate storage, and germination testing are imperative to secure optimal growth. The cost-intensive nature of aircraft rental, equipment maintenance, fuel, and logistical aspects further compounds the challenge, demanding judicious planning for cost-effectiveness. Monitoring and evaluation complexities arise from the arduous task of tracking project progress, particularly in remote or inaccessible terrains. The ecological dimension accentuates these issues, as the inadvertent introduction of invasive or non-native species could disrupt indigenous biodiversity and ecosystems. Therefore, meticulous calibration and testing of delivery mechanisms are pivotal for consistent and even seed coverage. Addressing these interwoven challenges holistically is essential for optimizing the success of aerial seed dispersal initiatives and fostering ecological rejuvenation.

Future Prospects

1. **Technology advancements**: Continued technological advancements will increase the effectiveness and precision of aerial seed dispersal through the use of improved seed delivery systems, aerial mapping, and remote sensing. Better seed targeting, monitoring, and evaluation made possible by these developments will result in better restoration outcomes.
2. **Precision agriculture**: By combining aerial seed dispersal with precision agriculture techniques, seed placement and resource allocation could be greatly improved. Advanced sensors, drones, and data analytics can help identify areas that require particular restoration efforts, enabling targeted management strategies and precise seed distribution.
3. **Native species restoration**: The use of native plant species for ecological restoration should be prioritized under this technique. Enhancing biodiversity, ecosystem resilience, and the delivery of ecosystem services are all benefits of restoring native plant communities. It will be essential to continue research and efforts to find appropriate native seed sources and grow them for aerial dispersal.
4. **Climate change adaptation:** Ecosystems' ability to adapt to climate change can be greatly aided by aerial seed dispersal. The restoration and improvement of ecosystem functions in a rapidly changing environment can be facilitated by choosing seed species and varieties that are resistant to changing climatic conditions, such as drought, heat, or increased pest pressure.
5. **Collaborative partnerships**: Future initiatives for aerial seed dispersal will be driven by partnerships among local communities, non-profit organizations, and governmental agencies. Sharing resources, expertise, and knowledge will improve the efficacy of restoration efforts and guarantee the long-term viability of projects.
6. **Ecological connectivity**: Aerially dispersed seeds can aid in facilitating movement and gene flow for wildlife populations by establishing vegetation corridors, supporting ecosystem resilience and adaptation.
7. **Restoration of degraded landscapes**: This technique can be an effective tool for restoring degraded landscapes, including mining sites, post-industrial areas, and abandoned agricultural lands. Aerial dispersal has the potential to speed up the restoration process and enhance ecosystem services by rapidly covering large areas with a variety of seed mixtures.
8. **Research and innovation:** Future development will be fueled by ongoing research and innovation in seed encapsulation technologies, aerial seed dispersal techniques along with seed germination and establishment techniques.

Conclusion

Aerial seed dispersal has enormous potential for extensive ecological restoration and land rehabilitation projects. Large-scale reforestation, improvement of biodiversity, and the restoration of damaged landscapes are all made possible by its efficient and precise seed distribution. Despite obstacles like weather dependence, seed viability and financial constraints, ongoing technological advancements and stakeholder cooperation offer hope for the future of aerial seed dispersal. The effectiveness and resiliency of aerial seed dispersal projects can be further increased by using native seed species in conjunction with strategies for adapting to climate change. For knowledge sharing, resource mobilization, and long-term project sustainability, collaborative partnerships between governments, organizations, and local communities will be essential. Additionally, community involvement and citizen science programs can promote a sense of ownership and stewardship, enabling people to support ecological restoration efforts.

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