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Opinion

Strategies for the Management of Aggressive Invasive Plant Species

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Abstract: Current control methods for invasive alien plants (IAPs) have acceptable short-term outcomes but have proven to be unfeasible or unaffordable in the long-term or for large invaded areas. For these reasons, there is an urgent need to develop sustainable approaches to control or restrict the spread of aggressive IAPs. The use of waste derived from IAP control actions could contribute to motivating the long-term management and preservation of local biodiversity while promoting some economic returns for stakeholders. However, this strategy may raise some concerns that should be carefully addressed before its implementation. In this article, we summarize the most common methods to control IAPs, explaining their viability and limitations. We also compile the potential applications of IAP residues and discuss the risks and opportunities associated with this strategy.

Keywords: invasive alien plants; waste from invasive plants; waste use; alternative strategies; sustainable long-term management

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1. Introduction

Scientific studies over the last few decades have highlighted invasive alien plants (IAPs) as one of the major threats to ecosystems [1–3], especially those growing in protected areas [4,5]. Plant invasions are mainly influenced by direct (e.g., by transport propagules) or indirect (e.g., by altering land use) human actions that involve moving plants around the world for different purposes [6]. For example, many exotic plant species were planted to provide products and benefits that support livelihoods [7]. Once established in a new region, some exotic plants rapidly expand and become invasive, causing significant losses in biodiversity, ecosystem functioning and services, socio-economic values, and human health in the invaded areas [8]. Invasive alien plant species have strong adaptability, fast reproduction, spreading capabilities, and other traits that contribute to their success in their new area. Climate change leading to environmental constraints can also increase opportunities for the establishment of IAPs, which are better able to acquire limited resources or use resources more efficiently than native plant species [9].

Invasive alien plant species have colonized almost all types of terrestrial ecosystems and aquatic environments worldwide, except for Polar biomes. For example, *Acacia* spp. in Mediterranean areas [1], *Prosopis* spp. in arid environments [10], *Carpobrotus* spp. in coastal areas [11], *Robinia pseudoacacia* L. and *Ailanthus altissima* (Mill.) Swingle in mixed forests [12], *Oxalis pes-caprae* L. in ruderal and agricultural lands [13,14], and *Eichhornia crassipes* (Mart.) Solms in water bodies and courses [15,16]. Invasive plants can form homogeneous stands that have significant impacts on both the above and belowground compartments of invaded ecosystems [17–19]. These impacts include changes in resident plant communities and soil microbes [17,18,20,21], animal populations [22,23], soil properties and nutrient cycling [24,25], fire regimes and water flow [2,23,26], and biotic interactions [27,28]. In addition, IAPs can threaten human health and the socio-economy of the region [29]. However, the economic costs associated with the detrimental impacts of IAPs remain largely unknown. According to the most recent database of invasion costs (InvaCost), the economic costs of the biological invasion reached USD 1.22 trillion in the USA [30] and EUR 116.61 billion in Europe [31] between 1960 and 2020, with a clear dominance of damage costs over management expenditure [32], focusing on eradication and control actions [33]. In the Mediterranean Basin as well as in Europe, *Ambrosia artimisiifolia* L. is the costliest IAP [31,34]. Moreover, the future overall invasion costs are expected to increase, which emphasizes the urgent need to allocate more resources for managing invasive species.

Here, we aim to (i) compile current methods used for controlling and managing IAPs, enumerating their viability and main weaknesses, (ii) present potential applications of IAP waste, and (iii) discuss the risks and opportunities associated with implementing a strategy for using IAP waste which could help to reduce the costs associated with their control.

2. Current Methods to Control Invasive Plants, Their Viability, and Problems

Some IAPs can have positive effects in several areas, including agriculture, the ornamental horticulture industry, and wood production, but their use can result in harmful effects, representing a conflict of interest in their management [35,36]. Harmful IAPs need to be controlled due to the magnitude of their environmental, economic, social, and aesthetic impacts. In dramatic cases of invasion, when IAPs show high vegetative reproduction and are widely distributed across large areas, eradication is extremely difficult and expensive. Therefore, confining invasive populations and limiting their spread through effective strategies should be prioritized.

Traditional management methods for terrestrial and aquatic IAPs include physical (manual or mechanical) methods such as pulling and digging, debarking, harvesting [37], mowing and tilling [38], prescribed fire [39], soil solarization [40], construction of barriers to limit the spread of aquatic weeds [41], usage of chemical (e.g., herbicide application [37,42,43]), biological control [37,44], or a combination of several methods [45,46]. The feasibility of each method depends on the species, the extent of invasion, the characteristics of the habitat, and the effectiveness of the control methods [47]. A recent Australian study based on the stakeholders' perspective in the management of IAPs noted that decision-makers are more confident in the use of chemicals than biocontrol and mechanical methods in the control of IAPs and believe that it is more feasible to control succulents and herbs/shrubs than monocots and woody vines [48].

Although the existing control methods often produce relatively good short-term outcomes, they are ineffective in eradicating IAPs in the long-term if not applied periodically [3,49,50]. For example, a recent study by Froeschlin et al. [51] in South Africa, a pioneering country in managing IAPs, noted that after 10 years of adopting a combination of control measures (mulching, herbicides, and the sowing of native species) to restore invaded areas, IAPs were not totally extirpated, indicating the need to improve techniques and implement additional efforts to eliminate them. Also, Duarte et al. [52] stressed the importance of frequent follow-up actions to reduce the abundance of *Acacia longifolia* (Andrews) Willd. in coastal dunes. Success in containing the dispersion or ultimately eradicating IAPs requires consistent post-surveillance and follow-up actions within an integrated strategy framework, which represents a huge challenge in terms of the available budget and execution timeframe [53]. In the absence of ongoing management, escaped individuals from the management can act as new focal dispersal points [51], leading to potential recolonization of the area and a loss of previous control efforts. However, the long-term management of IAPs is often neglected in part due to unaffordable costs for sustained efforts or a lack of interest after controlling the initial target population. Hence, it is necessary to adopt a more economical and efficient strategy to manage IAPs, for example, by deriving benefits from the management of plant invasion.

Besides economic problems, traditional methods also lead to social and environmental side effects. The use of synthetic herbicides can negatively affect human health, including neurological, reproductive, and respiratory diseases, diabetes, and even cancer [54], and the environment by reaching non-target organisms [55], raising concerns about their use. The repeated use of chemicals may also lead to invasive populations developing resistance to herbicides [56]. On the other hand, the introduction of generalist biological control agents can infect non-target species, causing a decline in their populations [57]. Another drawback common to most traditional control methods and anticipated in the previous paragraphs is the poor cost-effectiveness of the relationship between the invader spreading and the controlled area or the eradication time. As an example, the eradication of *Alliaria petiolata* (Bieb.) Cavara and Grande from an area of Adirondack Park (United States) was predicted to take 11 years with 100% effective control or more than 50 years with only 90% effective control [58]. In general, the management of IAPs is very expensive [31], with control strategies still prioritizing key landscape points to disrupt invasion connectivity and likely reduce costs without covering the whole area [59]. Even the long-term and well-designed South African program "Working for Water" is far from controlling the entire estimated invaded area [60]. Such limitations with frequent uncertain outcomes make traditional control methods unsafe, unfeasible, or unaffordable for large areas.

Recently, proactive strategies such as avoiding introduction, early detection, and rapid intervention (Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014), prioritization of control actions, and citizen awareness have been proposed as key to prevent the spread of IAPs and reduce their negative impacts and control costs [37,61–63]. Involving volunteers is also an important component of monitoring and controlling IAPs [64], helping to reduce costs while increasing public awareness [65]. However, this solution is impractical for the rapid control of infested or heavily invaded areas since it is necessary for there to be continuous engagement and training of the volunteers [66]. Therefore, designing cooperative strategies in biosecurity among affected countries [36] is essential for the development of more cost-effective actions against IAPs. Despite these recent strategies preventing the introduction of new exotics, which are totally necessary and welcome, they are still in their infancy and do not greatly improve the control of IAPs already established. For these reasons, it is crucial to find alternative strategies to control current aggressive IAPs in a more sustainable way.

3. Potential Applications of IAP Waste from Management Actions

The use of waste generated by the removal of aggressive IAPs, with the objective of reducing the large costs associated with the control of these species, is a viable alternative. The use of invasive waste can provide novel value-added products, resulting in not only profits for society but also helping to preserve local biodiversity and stimulate the long-term management of invaded areas [67]. With this approach, it would be possible to partially recover invested funds that would otherwise be lost [42,67,68]. Moreover, it prevents the use of limited resources by introducing underused material into the system, which aligns with the circular bioeconomy rationale (Figure 1) and Sustainable Development Goals 12 (responsible consumption and production) and 15 (life on land) of the 2030 Agenda.

The waste from IAPs exhibits specific properties (functional, biological, medicinal, etc.) that can be used directly or serve as a basis for new products, as summarized in Table 1. For example, waste biomass, especially that from invasive legumes, but not only them, is primarily a source of nutrients that can be used as fertilizers, horticultural substrates, or soil amendments in agriculture either directly or after a composting process [69–103]. Invasive plants with allelopathic/phytotoxic effects, such as *Acacia dealbata* Link, *Solidago canadensis* L., or *S. gigantea* Aiton, can provide compounds with pesticidal or biostimulant effects appropriate for agricultural purposes [104–107]. Some IAPs are also a source of bioactive compounds with beneficial antioxidant, antimicrobial, nutraceutical, pharmacological, cosmetic, or therapeutical-related applications (e.g., [16,108–132]). Invasive waste can also be used to produce bioenergy, namely bioethanol, biogas, or wood fuel (e.g., [133–148]), biochar or charcoal for different purposes (e.g., [149–153]), or animal feed (e.g., [154–157]. Some authors also suggest the use of IAPs for effluent treatments (e.g., [158–165]), paper and packaging materials (e.g., [166–170]), building materials [171], natural fiber composites [172], and bio-adsorbents for textile dyes or others [173–180].

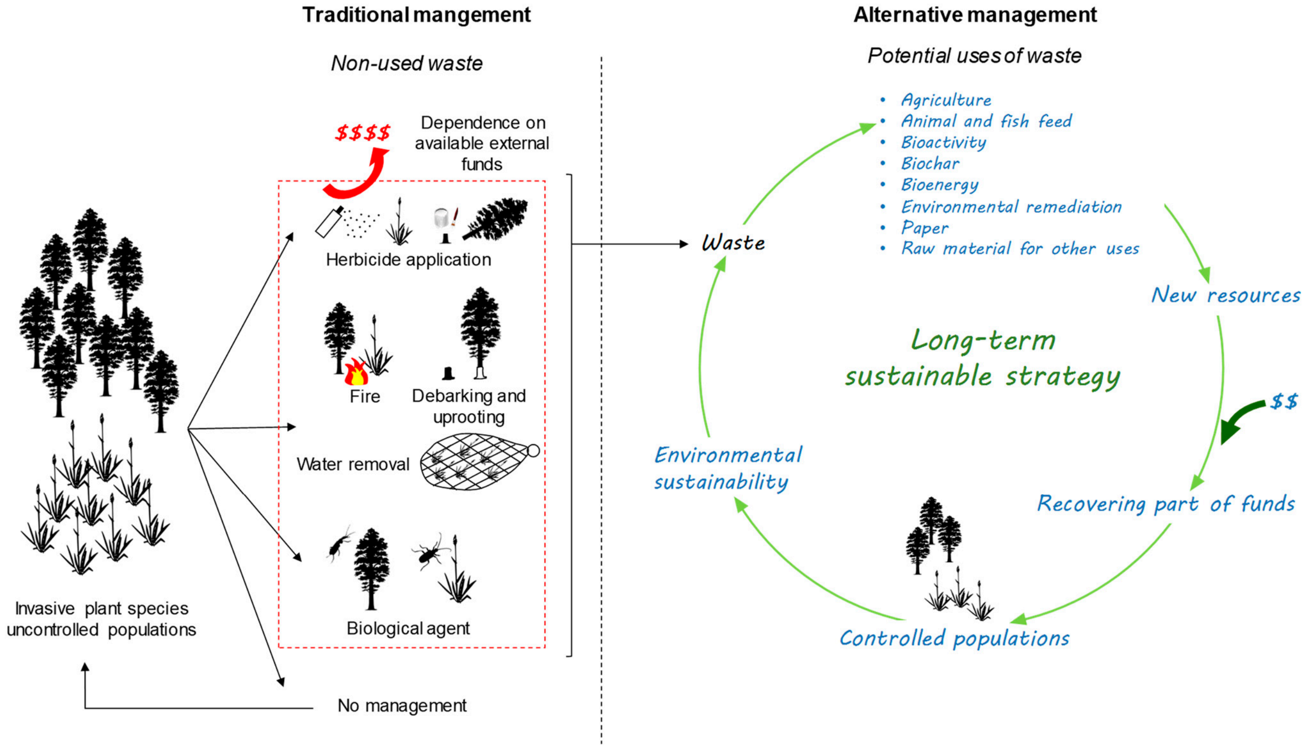

Figure 1. Scheme for the proposed management for the control of highly invasive alien plants.

Table 1. Reported uses for invasive plant species.

Potential Use	Invasive Plant Species	Reference
Agriculture-related uses (fertilizers, compost, vermicompost, bioherbicides, etc.)	*Acacia dealbata* Link, *Acacia longifolia* (Andr.) Willd., *Acacia melanoxylon* R.Br., *Acacia podalyriifolia* A.Cunn. ex G.Don, *Acacia* spp., *Ailanthus altissima* (Mill.) Swingle, *Ageratina adenophora* (=*Eupatorium adenophorum*) (Spreng.) R.M.King and H.Rob., *Albizia julibrissin* Durazz., *Azolla filiculoides* Lam., *Eichhornia crassipes* (Mart.) Solms, *Fallopia japonica* (=*Reynoutria japonica*) (Houtt.) Ronse Decr., *Hedychium gardnerianum* Sheppard ex Ker Gawl., *Ipomoea staphylina* Roem. and Schult., *Lespedeza cuneata* (Dum.Cours.) G.Don, *Litsea glutinosa* (Lour.) C.B.Rob., *Myriophyllum* spp., *Parthenium hysterophorus* L., *Prosopis juliflora* (Sw.) DC., *Tithonia diversifolia* (Hemsl.) A.Gray, *Typha latifolia* L.	[69–107]
Bioactivity (pharmaceutical, nutraceutical, cosmetic, etc.)	*A. dealbata*, *A. melanoxylon*, *A. adenophora* (=*E. adenophorum*), *A. altissima*, *Amaranthus retroflexus* L., *Calotropis procera* (Aiton) A.W. Aiton, *Disphania ambrosioides* (L.) Mosyakin and Clemonts, *Dittrichia graveolens* (L.) Greuter, *E. crassipes*, *Erigeron annuus* (L.) Pers., *F. japonica* (=*R. japonica*), *Gleditsia triacanthos* L., *Heracleum mantegazzianum* Sommier and Levier, *Polygonum cuspidatum* Siebold. and Zucc., *Solidago canadensis* L., *Solidago gigantea* Aiton, *Spartina anglica* C.E.Hubb., *Tradescantia fluminensis* Vell., *Ulex europaeus* L.	[16,81,87,88,92,104, 108–132]

Table 1. *Cont.*

Potential Use	Invasive Plant Species	Reference
Bioenergy (bioethanol, biogas, wood fuel, etc.)	*A. dealbata*, *A. adenophora* (=*E. adenophorum*), *A. altissima*, *C. procera*, *Dioscorea bulbifera* L., *E. crassipes*, *Eucalyptus globulus* Labill, *F. japonica* (=*R. japonica*), *H. mantegazzianum*, *Impatiens glandulifera* Royle, *Limnocharis flava* (L.) Buchenau, *Phragmites australis* (Cav.) Trin. Ex Steud., *Phalaris arundinacea* L., *Schinus terebinthifolius* Raddi, *S. gigantea*, *Spartina alterniflora* Loisel., *Typha* spp.	[81,83–88,133–148]
Biochar (activated carbon and biochar precursors)	*A. dealbata*, *Acacia auriculiformis* A.Cunn. ex Benth., *A. adenophora* (=*E. adenophorum*), *A. altissima*, *Alternanthera philoxeroides* (Mart.) Griseb., *D. bulbifera*, *E. crassipes*, *Leucaena leucocephala* (Lam.) de Wit, *Mimosa pigra* L., *P. juliflora*, *S. terebinthifolius*, *S. canadensis*, *S. gigantea*, *S. alterniflora*	[81,87,88,142,149–153]
Feed (animal or fish)	*A. altissima*, *C. procera*, *Cyperus* spp., *E. crassipes*, *H. gardnerianum*, *Hottonia* spp., *Lemna minor* (L). Griff, *Leucaena* spp., *Myriophyllum* spp., *Nasturtium* spp., *Pistia stratiotes* L., *Pittosporum undulatum* Vent., *P. juliflora*, *S. alterniflora*, *Typha* spp.	[81,85–87,94,154–157]
Environmental remediation (wastewater treatment, etc.)	*A. dealbata*, *A. altissima*, *C. procera*, *E. crassipes*, *Myriophyllum* spp., *P. arundinacea*, *Phragmites australis* (Cav.) Trin. ex Steud., *Pistia stratiotes* L., *Typha* spp.	[83,85,86,93,94,115,146, 158–165]
Paper-related uses (handmade, etc.)	*A. altissima*, *E. crassipes*, *Fallopia x bohemica* (J.Chrtek and A.Chrtková) J.P. Bailey, *F. japonica* (=*R. japonica*), *Fallopia sachalinensis* (C.F. Schmidt) Ronse Decr., *S. canadensis*, *S. gigantea*, *Robinia pseudoacacia* L., *Rudbeckia laciniata* L.	[15,78,87,166–170]
Raw materials to produce different products (biorefineries, nanoparticles, resins, crafts, building materials, eco-bases, textile dyeing, etc.)	*A. dealbata*, *A. longifolia*, *Arundo donax* L., *C. procera*, *E. crassipes*, *F. japonica* (=*R. japonica*), *Mikania micrantha* Kunth ex H.B.K., *Pennisetum setaceum* (Forssk.) Chiov., *Ricinus communis* L., *Typha angustifolia* L.	[85,86,88,115,121,132, 145,171–180]

4. Remarks on the Risks and Opportunities of Adopting the Use of Waste from IAPs

The use of waste from IAPs to control invasive populations, although not completely new, is advocated by several authors, as mentioned in Table 1 [92,126]. This idea is not broadly accepted among plant invasion ecologists [181], who argue that it can promote the cultivation of IAPs or facilitate their spread due to negligence in the treatment/transport of waste. This concern is valid given that plant invasion is a sensitive issue, and using IAPs poses the risk of incentivizing its growth instead of its control [182]. However, when invasion achieves a dramatic level and traditional control methods prove to be physically or economically insufficient or fail over time, which is associated with the inability to conduct follow-up actions after the end of a management project, the use of IAP waste could be viewed as a sustainable and viable solution to control and restrict the expansion of aggressive IAPs (Figure 1). The control of widespread IAPs, such as Australian acacias (*Acacia* spp.), water hyacinth (*E. crassipes*), or pampas grass (*Cortaderia selloana* (Schult. and Schult.f.) Asch. and Graebn.) [9,20,24,183], which have high vegetative reproduction and/or produce huge quantities of long-lived seeds that make their control difficult even after clearing an invaded area [67], generates large quantities of waste, often left on-site or burned for energy purposes [184]. The abandonment of the plant material may be a fire hazard [2,185], which can also contribute to the death of native plants and increase the risk of re-invasion [2], resulting, in turn, in the loss of control action benefits. In these situations, we suggest that using the waste from control actions is a reasonable approach to manage the overabundance of these IAPs in the long-term. The implementation of this approach may reduce the continuous spread of IAPs and contribute to the partial recovery of management funds, creating conditions for the sustainability of the process (Figure 1). In addition, the conversion of waste biomass from IAPs into new, useful products can promote zero-waste and circular economy approaches [186]. The potential uses of waste derived from IAPs have gained increasing interest in the last years, as summarized in Table 1. The majority of these studies were performed on a laboratory scale and focused on the potential of IAPs for further investigation and application in different areas, but relatively few studies include a cost–benefit analysis of using waste from IAPs. The work of Mudavanhu et al. [187] is one of the studies that discuss the economic implications of using the waste of *Acacia cyclops* A. Cunn. ex Don fil. for electricity generation in South Africa and concluded that it is a viable and feasible option in comparison with electricity production by diesel generators. On the contrary, Melane et al. [188], also in South Africa, observed that the costs of using biomass of seven non-woody IAPs, namely *Arundo donax* L., *Lantana camara* L., *Solanum mauritianum* Scop., *Atriplex nummularia* Lindl., *Cestrum laevigatum* Schlecht, *Senna didymobotrya* (Fresen.) H. S. Irwin and Barneby, and *Chromoleana odorata* (L.) R.M.King and H.Rob, were very high when compared to woody IAPs, suggesting that these IAPs are not a profitable resource for the production of electricity. Another study conducted by Valen [189] with the aim of investigating the cost–benefits of *Arundo donax* as feedstock for the pulp and paper industry in California, indicated an average annual profit of ca. 60% of removal expenses, which is an encouraging indicator of the financial viability of the process. As indicated by Ortega et al. [172], it is important to emphasize that the economic benefits achieved by using IAP biomass should be only to minimize the costs of their management and control and ultimately contribute to the reduction of the area occupied by these species. However, complete economic analyses assessing all aspects of using IAP waste, including management actions, waste transport, waste processing, and the benefit of the final product, are still lacking.

The use of invasive waste should be adopted within a clear regulatory framework to avoid bias in the utilization of this waste [182]. As stated before, the cultivation of IAPs is legally prohibited (Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014), but the use of IAP waste derived from control actions lacks legal policies. To ensure that this strategy is properly applied, it is a prerequisite that a long-term management plan for IAPs is applied. In addition, it is necessary to select a control method (please see Section 2) that minimizes the risk of re-invasion and implement a monitoring plan for the controlled area after management actions. A set of recommendations for control, transport, and waste disposal after the control takes place should also be considered to avoid the dispersion of new propagules and the re-establishment of the invader. For example, control actions should take place when plants have no flowers or fruits/seeds to prevent seed dispersal. The location of disposal sites should be in areas with minimal possibility of IAP establishment, and the area should be monitored to prevent their spread. For IAPs that reproduce by seeds (e.g., *Acacia* spp. and *Cortaderia selloana*), the plant material should be left on site to dry. For IAPs that present viable (root or stem) fragments (e.g., *Carpobrotus edulis* and *Eichhornia crassipes*), the plant material should be left on site with the roots upward to prevent them from contacting the soil. In both situations, transport should occur when all plant material is completely dry, and the operation should be monitored for the presence of any type of viable structures.

In summary, the use of waste from IAPs is a strategy that feeds on and completes traditional control actions to facilitate the management of aggressive IAPs. However, this strategy should only be conducted in specific and dramatic invasion cases, when traditional control methods have failed over time, and should be conducted under strict regulations. This strategy should be accompanied by a complete economic analysis covering the entire IAP management and use of the waste process.

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