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Precision agriculture can foster cropland weed diversity and protect endangered species

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Review

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Abstract

Weed diversity plays an important role in the functioning of agroecosystems. Moreover, a number of endangered/threatened plant species occur as weeds in arable fields and/or field boundaries. Agricultural intensification has imposed negative consequences on weed diversity in general, and the survival of the endangered/threatened plant species in particular. The objective of this review is to provide a theoretical framework for promoting cropland weed diversity through precision agriculture. A systematic review was conducted based on literature analysis, existing knowledge gaps, and current needs to identify a suitable approach for promoting cropland biodiversity while protecting crop yields. While nonchemical weed management methods and economic threshold–based approaches are touted to improve weed diversity, they are either ineffective or insufficient for this purpose; long-term economic consequences and the risk of weed adaptation are major concerns. A plant functional trait-based approach to promoting weed diversity, one that considers a plant's ecosystem service potential and competitiveness with the crop, among other factors, has been proposed by researchers. This approach has tremendous potential for weed diversity conservation in commercial production systems, but field implementation has been limited thus far due to our inability to selectively control weeds at the individual-plant level. However, recent advancements in computer vision, machine learning, and site-specific weed management technologies may allow for the accurate elimination of unwanted plants while retaining the important ones. Here, we present a novel framework for the utilization of precision agriculture for the conservation of cropland weed diversity, including the protection of endangered/threatened plant species, while protecting crop yields. This approach is the first of its kind in which the control priority is ranked on an individual-plant basis, by integrating intrinsic weed trait values with field infestation characteristics, while management thresholds are tailored to specific goals and priorities.

The Benefits of Cropland Weed Diversity

Weeds are an elemental part of biodiversity in croplands (Gerowitt et al. 2003; Petit et al. 2011), which includes weeds within arable fields, field edges/margins, and buffer strips. Many higher taxa feed on weeds or use them as shelter. The food web that depends on weeds includes insects, mammals, birds, and even top predators at the higher trophic levels. For example, carabids have been known to rely on weed seeds (Carbonne et al. 2020; Frei et al. 2019). Birds eat the weed seeds and feed their juveniles with insects, which are often supported by the weed plants (Holland et al. 2006). At much higher levels, raptors eat mammals feeding on weeds (López-Darias and Nogales 2016). These are just a few examples. The same might be true for soil-dwelling organisms that use weed seeds as a food source and become an integral part of the food web. Diverse weed communities are characterized by a multitude of functional traits that contribute to ecosystem services such as pollination, nutrient cycling, erosion prevention, and improving soil microbial diversity, among others, and thereby serve as an important ecological good. For instance, the ability of weeds to attract pollinators and beneficial insects may help enhance agricultural productivity (Petit et al. 2011). Cropland weed diversity also includes endangered and/or threatened plant species, which are required to be protected by federal regulations (e.g., [EEA] European Environment Agency, 2023; USEPA 2024b). While the full extent to which weeds and weed seeds support various organisms in agroecosystems is yet to be fully understood, the role of weed plants in maintaining healthy agroecosystems has been well recognized (Gaba et al. 2020; Ilic 2023; Marshall et al. 2003; Storkey and Neve 2018). Despite the well-known benefits of weed diversity in crop fields, yield losses are typically a concern with uncontrolled weeds. However, it has been shown that diverse weed communities are less likely to reduce yield while supporting biodiversity (Adeux et al. 2019; MacLaren et al. 2019; Storkey and Neve 2018). Gaba et al. (2020) found a neutral relationship between crop yield and ecosystem

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multifunctionality associated with weeds. Likewise, Esposito et al. (2023) suggested that "neutral weed communities" can coexist with crops without affecting yield and quality.

The Impact of Modern Agriculture on Weed Diversity

The widespread adoption of herbicide-dominant weed management in recent decades has made weed management a relatively simple task. In particular, the ability to use broad-spectrum herbicides in herbicide-tolerant cropping systems has allowed for a level efficacy of in-crop weed control never witnessed before. Such intensive management has accelerated a reduction in the number and abundance of weed species present in these systems (Schütte et al. 2017). This development in weed management has coincided with other facets of agricultural intensification, such as an increase in the reliance on synthetic fertilizers, with significant negative impacts on weed diversity (Storkey et al. 2010; Travlos et al., 2018), and the associated diversity of other organisms that rely on them. In Europe, the majority of once-common weed species have declined dramatically. For example, in central Germany, Meyer et al. (2013) reported a 50% reduction in the mean number of in-field weed species between the 1950s/1960s and 2009. The reduction in weed community diversity was complemented by an increase in the dominance of a select annual weed species that have the ability to effectively utilize synthetic nitrogen applications and are highly competitive with crops, leading to persistent weed infestations (Andreasen et al. 2018). Moreover, intense herbicide selection pressure within these systems has resulted in the evolution and spread of herbicide-resistant weeds, selecting for even fewer dominant weed species (Hulme 2022; Peterson et al. 2018), further reducing the field-scale weed species diversity. In the southern United States, for example, Palmer amaranth (*Amaranthus palmeri* S. Watson), a prevalent herbicide-resistant weed, is now a dominant species in many production fields (e.g., Werner et al. 2020). Likewise, blackgrass (*Alopecurus myosuroides* Huds.) populations with widespread herbicide resistance in them have been dominating winter cereal production fields across Europe (e.g., Adamczewski et al. 2016; Delye et al. 2007; Keshtkar et al. 2015)

Existing Approaches and Their Limitations in Enhancing Weed Diversity

Sustainable Cropping Systems and Programs

Within the context of biodiversity, organic operations are known to promote overall biodiversity, especially the diversity of weed communities (reviewed in Hole et al. 2005), due to the generally higher weed occurrence in these systems. In conventional systems, several measures have been suggested as a means to enhance biodiversity, including the adoption of cover crops during the offseason (Finney and Kaye 2017), the maintenance of buffer strips in field margins (Birnbeck et al. 2025), and the allocation of set-aside lands (Schutz et al. 2022). In an extensive literature analysis, Haddaway et al. (2018) identified substantive bodies of evidence that establish the ecosystem service value of vegetative strips within and around agricultural fields. While these practices greatly help enhance biodiversity and offer valuable ecosystem services, these are not adequate to support alpha diversity (i.e., species diversity within a community at a local scale) and maintain local weed populations in the long term (Fried et al. 2009). In this regard, the ability to maintain within-field weed diversity is important and can be particularly valuable for the in situ conservation of endangered and threatened species. Further, the effect range of buffer strips to support beneficial organisms in the field is limited (Kujawa et al. 2020); thus, in-field weeds need to compensate for these effects (Serée et al. 2023). Moreover, the large spatial coverage of the crop fields compared with the relatively smaller field edges may also be an important factor in the extent of services offered. In fact, Köthe et al. (2023) argue that the negative spillover effects from in-field management could affect endangered species in the buffers, especially in areas proximal to the crop field. Within the European Union, there are government programs, such as eco-schemes, which are a component of the common agricultural policy (European Commission 2024), to incentivize in-field management strictly for biodiversity, but crop yield is not a priority with these schemes.

Economic Threshold (ET)

ET-based weed management is thought to support biodiversity conservation, as it allows for a certain density of weeds or groups of weed species to be left uncontrolled in the fields. However, this may not be a wise strategy, because the leftover weeds are not necessarily the most beneficial species. Moreover, ET-based weed control is strictly based on estimated crop yield loss in the current season, and using this measure for biodiversity provision may be counterproductive in the long run, although species-specific ETs may be useful for this purpose. In herbicide-dominant systems, allowing generic ET-based weed escapes could be very risky, because such escapes either already contain resistant individuals or have individuals with minor resistance contributing alleles with the potential for resistance evolution through recurrent selection. Thus, only reducing the intensity of chemical weed control while leaving everything else unchanged is expected to cause problems, and it may not be a sustainable approach to biodiversity enhancement in cropping systems.

Trait-based Management Recommendations

An approach to weed diversity conservation that takes into account specific weed traits, especially targeting in-field weed communities, has been proposed as a viable approach (Zingsheim and Döring 2024). While this goal has been around for some time, practical implementation of such a concept has been very challenging until now, because it requires technologies that can recognize individual species and selectively eliminate the undesirable ones (von Redwitz et al. 2025). Furthermore, the knowledge of relevant weed functional traits is still inadequate, with data originating from arable fields being particularly scarce. This information is important not only for biodiversity protection but also for preventing weed adaptation to sensor-based detection. Maintaining alpha diversity, which is the most complex and challenging to achieve, can be addressed by precision agriculture. Technological advancements allowing for individual plant–level management are expected to facilitate field adoption of the trait-based management approach, which holds promise for the near future. The specifics of how it could be carried out are discussed in the "Considerations for Field Implementation" section.

European versus North American Context on Cropland Biodiversity

The rationale and approach to managing weeds for biodiversity differ considerably between the agricultural systems in Europe and

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North America, particularly the United States. In Europe, there has been an emphasis on the promotion of alpha diversity not only on non-cropped land (i.e., field edges/strips) but also through in-field weed diversity conservation. This approach has been driven primarily by the European environmental programs that offer incentives for promoting biodiversity (Batáry et al. 2015). Agri-environmental schemes aiming at weed diversity are often adopted by small-scale operations that typically implement integrated weed management, incorporating chemical and nonchemical tactics. As a result, there is generally less risk for weed adaptation to occur within this approach to weed management and biodiversity conservation. Conversely, it is notable that weed resistance issues are high in systems that do not incorporate diversified practices.

In the United States, much focus on biodiversity and ecosystem services is placed on set-aside lands such as the Conservation Reserve Program (CRP) lands. The CRP lands are generally less productive parts of a farm that are planted with a mix of preferred plant species with high value for biodiversity. However, these mixes do not typically include beneficial arable weed species native to the locality. Moreover, these sites are routinely managed for weeds, which may inadvertently harm beneficial and endangered/threatened species already present, as current management practices do not aim at protecting these species. Thus, CRP lands cannot be regarded as a complete substitute for the in-field plant biodiversity. The CRP program is voluntary, and the participants receive incentive payments from this federal program. In 2023, a total of 24.8 million acres of land were enrolled in the CRP program across the country, with more than US$1.77 billion in incentive payments distributed to about 667,000 producers and landowners (USDA-FSA 2024).

The concept of buffer strips is gaining importance in the United States as an additional means to enhance biodiversity. Buffer strips are small strips within agricultural fields (or field edges/margins) that are permanently dedicated to native grasses and other beneficial vegetation. Buffer strips can support arable weeds with biodiversity value. Circular buffer strips have been shown to provide a multitude of ecosystem benefits, including biodiversity enhancement, under center-pivot irrigation systems (Angadi et al. 2016). A particularly notable, but underexplored, benefit of the buffer strips is the protection of endangered and threatened species in these sites. The recent Endangered Species Protection Act in the United States (USEPA 2024a) is expected to restrict the use of certain herbicides. Within this context, there is a growing interest in the use of buffer strips and set-aside lands to support rare plants and those that support other endangered/threatened organisms.

As discussed earlier, relying on generic ET-based weed management for biodiversity protection may not be ideal, especially within the U.S. context. Many of the conventional production fields in the United States are large and rely heavily on herbicide-dominant weed management programs. It is also likely that these production systems are currently dominated by fewer but problematic weeds, with limited alpha diversity to start with. In these systems, the weed diversity found around crop harvest may predominantly include resistance-prone individuals, especially the ones having minor resistance-endowing alleles that allowed them to survive sublethal herbicide exposure (Bagavathiannan and Norsworthy 2012).

In both the European and U.S. contexts, precision agriculture can bring enormous benefits to establishing and sustaining field-scale measures for cropland weed diversity protection. In the United States, as emphasis on in-crop weed diversity continues to grow, especially within the framework of endangered/threatened plant species protection, precision agriculture can offer a convenient means for the selective elimination of unwanted plants within production fields. The same can be accomplished for the selective elimination of problematic plants in buffer strips. Precision agriculture–based in-crop weed diversity conservation may also be valuable for the EU because of insufficient land availability for set-aside lands for this purpose. Where set-aside lands are feasible, regardless of the EU/U.S. context, precision agriculture can allow for periodic vegetation monitoring and elimination of competition from unwanted species, including the management of invasive species.

Precision Agriculture and Weed Diversity Conservation

With the recent advancements in computer vision and machine learning, precision agriculture has been touted as having enormous potential to promote weed diversity in croplands. This can be accomplished through selective elimination of problematic weeds while still allowing for the beneficial weeds to flourish, following a preestablished decision framework (Figure 1). While the concept of trait-based weed management and diversity conservation is appealing, and considerable research progress has already been made in trait value assessment over the past decade (e.g., Schatke et al. 2024; Storkey and Westbury 2007; Yvoz et al. 2021), technology that enables selective weed control has not been available. However, current advancements toward individual plant–level weed recognition are expected to allow for this possibility in the near future (reviewed in Esposito et al. 2021; von Redwitz et al. 2025). Precision technologies can even allow for new approaches to biodiversity conservation, such as miniature set-aside patches within large production fields. This novel concept can take advantage of randomly occurring low-productivity patches within crop fields and dedicate those areas to biodiversity conservation. These miniature patches can be easily maintained and managed through the implementation of precision farming technologies. Even for the set-aside lands, including buffer strips, precision technologies will be valuable for site-specific treatment of invasive and unwanted plant species, while allowing desirable species to thrive, which has been a major challenge for their continued maintenance.

Considerations for Field Implementation

Field implementation of precision agriculture–mediated weed diversity enhancement requires that progress be made in three core areas: (1) establishing a management decision framework (illustrated in Figure 1) that incorporates two key components: (a) management importance values and categories developed based on the biological and field infestation characteristics of individual weeds and (b) a decision support system that informs management action on individual weed plants based on management goals (both short-term and long-term) of the practitioner; (2) developing weed image datasets and machine learning algorithms for species-level recognition that can be deployed across diverse geographic settings; and (3) developing site-specific management capabilities that can precisely eliminate specific weed plants based on the preestablished decision framework.

Management Decision Framework

Efforts have been ongoing over the past decade, particularly in Europe, to develop management importance rankings for different

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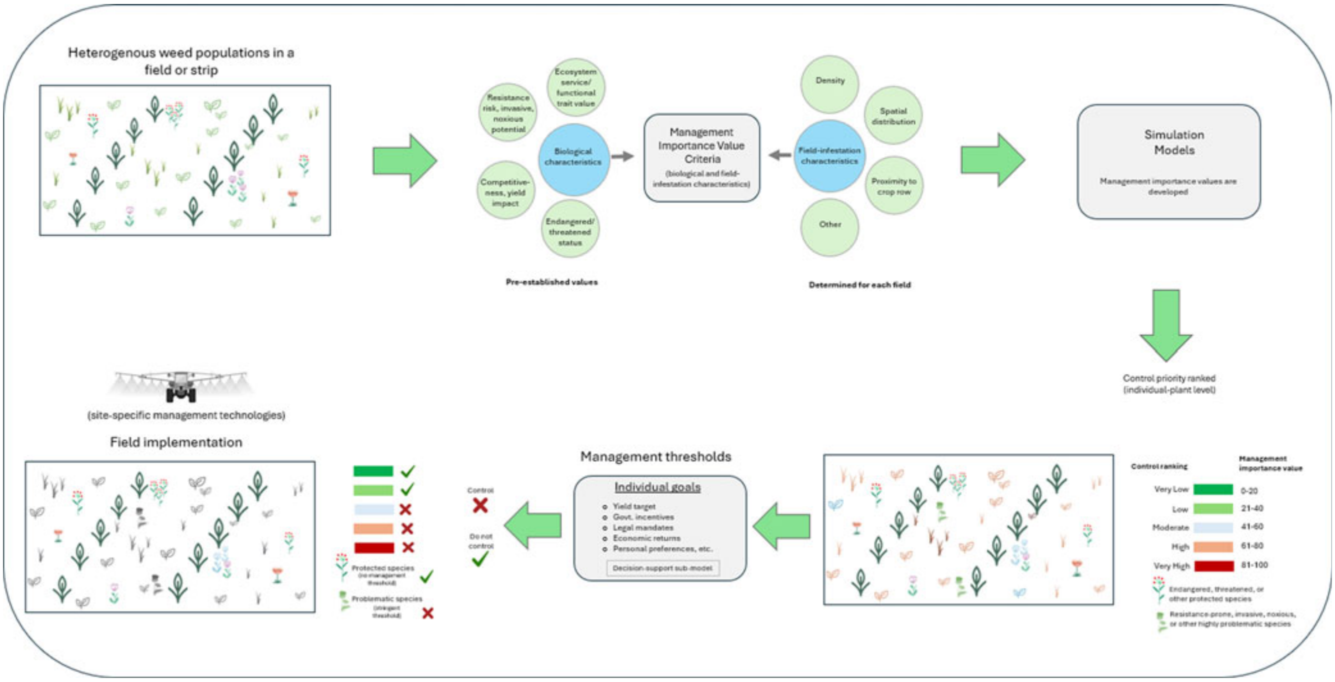

Figure 1. A conceptual framework illustrating the utilization of precision agriculture for the conservation of cropland weed diversity.

weed species. The goal is to identify and conserve weeds that are beneficial for biodiversity and, in the best case, do not conflict with agronomic interests. Merfield (2022) suggested the name "aliae plantae" to describe those plants that are non-problematic, which essentially make up the "neutral weed communities" that do not harm the crop (Esposito et al. 2023). Management importance rankings can be established by assessing their ecosystem service/ functional trait value, endangered/threatened status, competitiveness, risk of herbicide resistance, among others attributes. Schatke et al. (2024) present an approach for generating site-specific management maps based on a selection of these traits. However, because the impact of a specific plant always depends on the situation in which it occurs (including density, spatial distribution, crop type, proximity to crop row, etc.), the ranking for management importance must consider the field characteristics as well. In this regard, employing simulation models will be imperative to adequately account for weed–crop interactions (e.g., von Redwitz et al. 2024) and long-term biological outcomes (reviewed in Bagavathiannan et al. 2020). The research knowledge required for establishing the importance rankings, nevertheless, has been scarce. Zingsheim and Döring (2024) have indicated that the lack of functional trait databases for weed species, which are more specific than existing databases such as TRY (https://www.try-db.org; Kattge et al. 2020), is a major research gap in achieving this goal.

The importance values can be grouped into a range of predetermined categories, and ranked based on control priority, from very low to very high. This value can be very high (>90) for highly problematic weeds. Further, the management importance values can be plastic to account for ongoing weed adaptive evolution to management and climatic conditions. These can be updated on an annual basis and captured in both the biological and field infestation characteristics shown in Figure 1. The decision on the rigor of weed control to be implemented in the field with respect to what categories of weeds will be controlled depends on individual management goals. These can be influenced by factors such as yield target, government incentives, legal mandates, economic returns, and personal choices. To this effect, varying management thresholds can be considered based on the needs and specific scenarios. For example, a "zero-tolerance" threshold can be chosen for highly problematic and resistance-prone weed species such as *A. palmeri* in the southern United States, as proposed by Barber et al. (2015). Likewise, weeds with high invasive potential, those classified as federal or state noxious weeds, or those mandated for removal by regulation can be assigned stringent management thresholds, even if they offer high biodiversity values. Endangered, threatened, or other weed species protected by regulation can be excluded from management by default. Nevertheless, endangered/threatened species are often expected to occur in low densities and are typically weak competitors with a negligible impact on crop yield. A decision support submodel can incorporate these criteria and indicate a "yes/no" decision on an individual-plant basis. As such, precision agriculture enables a redefinition of the "management threshold" concept, applicable at the species- or individual plant–level within a given field, making it more practical and aligned with specific priorities, a long-standing challenge in the field.

Weed Recognition

For the purposes of weed diversity conservation, species-level recognition is imperative, unlike a precision weed control scenario in which weed recognition based on a simple classification of non-crop vegetation can be sufficient. Current advancements in computer vision and machine learning have made it possible to achieve species-level plant recognition in complex agricultural scenes (Hu et al. 2021). However, such an application requires the development of annotated image datasets for various weed species in different cropping situations and geographic regions, which are currently lacking. These datasets should also include images of weeds at various growth stages and with morphological variations. The majority of the already existing image datasets, as well as the ones currently being developed, focus primarily on problematic weeds. Future efforts for weed image databases should also include weeds of biodiversity value to generate a more comprehensive database. With respect to species-specific recognition and management to achieve biodiversity goals, images captured in the visible spectrum (RGB) are expected to be sufficient, as machine learning that utilizes just these three bands (and other features) has been shown to offer enormous potential for species-level plant recognition in agricultural scenes (Coleman et al. 2024). Further, synthetic image generation pipelines can be utilized to augment raw images and introduce complex scenarios into the training image dataset (Sapkota et al. 2022). Various machine learning architectures need to be explored to develop robust algorithms for species-level weed recognition that can be robust across diverse biotypes and field scenarios.

Site-Specific Management

Site-specific weed management for biodiversity can take advantage of the recent developments in ground as well as aerial robotic technologies. Within the context of biodiversity management, one of the two broader approaches to site-specific treatments can be employed: the use of preestablished management maps (offline) or real-time recognition and management (online). With the first approach, spatial maps of RTK-GPS precision can be generated following weed recognition, for subsequent delineation of management sites based on preestablished decision criteria (discussed earlier). The advantage of this approach is that the decision-making process can take into account the field infestation characteristics, such as density, spatial distribution, and so on, of each plant. However, this is a two-step process wherein the first step involves imaging the entire field, analyzing the images, and delineating the management sites (i.e., mapping) for subsequent actuation in the next step. Thus, this approach can be time-consuming and may delay field operations. In the second approach, weed imaging, recognition, decision making, and actuation all happen in a real-time fashion. While this approach can be efficient, decision making does not take the field-scale weed infestation patterns into consideration. It may rather simply consider the ecosystem service/functional trait values of each species. It appears that the first approach, wherein the field-scale information is utilized for management decision making, is ideal for optimizing field-level thresholds for weed diversity conser vation. Management of weeds with a biodiversity focus also requires sophisticated actuators for site-specific treatment. Unlike in a conventional weed control scenario, where achieving crop selectivity from the management tool is generally easy given the spatial separation (row arrangements and wider spacings) and uniform densities, achieving the safety of beneficial weeds that are admixed among problematic weeds in random arrangements and densities can be challenging. Occlusions may make it very difficult to target certain weed plants without damaging others.

Research Needs and Action Plan

The prospect of selective weeding to allow for cropland biodiversity enhancement is promising, given the recent advancements in precision agriculture technologies. More research needs to be done to address key practical challenges that are still present. Plant functional traits need to be documented under field conditions for a wide variety of weeds, not just the highly competitive weed species. Traits especially important for agroecosystem functioning, such as pollen provision, seed production, and so on, need to be determined in a comprehensive way, in addition to competitive abilities. Modeling frameworks need to be developed to enable management decision making to achieve a biodiversity goal, while maintaining a preferred yield-loss threshold. Knowledge of the minimum number of individuals required for a species to sustain its population can greatly help with management decision making, but such numbers require the use of population dynamic models to simulate long-term population sizes.

A biodiversity threshold for weed management can be optimized based on the list of preestablished criteria discussed earlier, which should be regularly reviewed and updated. Effective species-level recognition requires the development of annotated weed-image datasets and recognition algorithms, not only for problematic species, but also for all species in a production environment. Thus, the expansion of weed and crop image datasets and algorithms through collaborative efforts is a critical need. Image analysis tactics to address occlusion in species mixtures need to be developed. Moreover, research investment on actuators, including different types of nozzles, mechanical tools, lasers, and so on, that are suitable for weed diversity management needs to be developed and field tested. It is important to note that weeds have the ability to develop adaptations to sensor-based detection, including plant mimicry, if this technique is used regularly (Coleman et al. 2023). However, there has been very limited research on this topic, and more research is imperative to understand the mechanisms by which this can happen. In this respect, the continuous expansion and updating of the image database will be essential.

The research needs identified here require coordinated efforts among researchers at the national and international levels. Interdisciplinary collaborations and partnerships among ecologists, weed scientists, and engineers are particularly vital. More importantly, engaging the tech industry from the beginning can help with the development of commercially viable technologies that meet the needs of the end users. Government policies can steer the implementation of this concept through appropriate incentives to farmers and the industry. Additionally, outreach and educational programs need to be developed to disseminate the importance of biodiversity in agroecosystems.

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