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Original Research

Using Activated Carbon to Limit Herbicide Effects to Seeded Bunchgrass When Revegetating Annual Grass-Invaded Rangelands[☆]

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ABSTRACT

Revegetation of exotic annual grass—invaded rangelands is challenging as annuals rapidly reinvade after control treatments. The most effective control of exotic annual grass is usually achieved with pre-emergent herbicides; however, species seeded simultaneously with these herbicides will likely experience nontarget damage. Thus, seeding often occurs 1 yr later to reduce herbicide effects to seeded vegetation, but by this time annual grasses may already be reinvading and limiting revegetation success. Activated carbon can be used to protect seeded species from herbicide damage because it has a high absorption capacity that can deactivate many herbicides. A pot study in a grow-room suggested that a pod containing activated carbon and seeds, herbicide protection pods (HPPs), may allow desired species to be seeded simultaneously with annual grass control with the pre-emergent herbicide imazapic. However, HPPs have not been field tested. We evaluated two seeding treatments (crested wheatgrass (*Agropyron desertorum* [Fisch.] Schult.) incorporated into HPPs and bare seed, simultaneously with an imazapic application to control annual grasses at two sites invaded by cheatgrass (*Bromus tectorum* L.) and medusahead (*Taeniatherum caput-medusae* [L.] Nevski). Crested wheatgrass abundance was 300% greater with HPPs compared with bare seed in late June. Imazapic application reduced exotic annual grass density at both sites by approximately half. These results suggest that HPPs can be used to allow desired species to be seeded simultaneously with imazapic application. This will allow seeded species a longer window to become established before experiencing pressure from exotic annuals and enable a single-entry approach compared with multiple entries currently employed to revegetate annual grass—invaded rangelands. Though further field testing is needed, in particular with multiple species and higher herbicide applications rates, these results suggest that HPPs could improve our ability to restore and revegetate exotic annual grass—invaded rangelands.
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Introduction

Exotic annual grass invasion and dominance is a critical threat to rangelands throughout the world (Purdie and Slatyer, 1976; Mack, 1981; D'Antonio and Vitousek, 1992; Brooks et al., 2004). Invasive exotic annual grasses are converting perennial-dominated plant communities into annual-dominated communities at an alarming rate. Invasion of exotic annual grasses increases fine fuel continuity and amounts (D'Antonio and Vitousek, 1992; Brooks et al., 2004). Exotic annual grasses also dry out earlier than native vegetation (Davies and Nafus, 2013). These alterations to fuels increases fire frequency, which favors exotic annual grasses over perennial vegetation and creates an annual grass-fire cycle (D'Antonio and Vitousek, 1992; Rossiter et al., 2003). Fires often start in annual grass communities and spread into adjacent uninvaded areas, thereby promoting exotic annual grass invasion of the uninvaded area. It is paramount that perennial vegetation be reestablished in these exotic-invaded rangelands to return ecologic and economic services and break the annual grass-fire cycle. Efforts, however, to establish perennial vegetation in exotic annual grasslands often fail. Thus, there is a critical need for seed enhancement technologies to overcome limitations to seedling establishment (Madsen et al., 2016).

In the sagebrush steppe ecosystem, invasion by cheatgrass (*Bromus tectorum* L.), medusahead (*Taeniatherum caput-medusae* [L.] Nevski), and other exotic annual grasses has increased fire frequency, degraded wildlife habitat, and reduced biodiversity (Mack, 1981; Davies, 2011). Exotic annual grasses are one of the primary threats to the sagebrush ecosystem and fauna dependent upon it. Reestablishing perennial grasses in exotic annual grass infestations is critically needed to protect the sagebrush ecosystem. Established perennial grasses are highly competitive with exotic annual grasses because of overlap in resource acquisition patterns (James et al., 2008). Perennial grasses can limit the spread of exotic annuals (Davies, 2008; Davies et al., 2010) and prevent reinvasion by exotic annual grasses after herbicide control treatments

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(Davies, 2010; Davies et al., 2015). At the seedling stage, however, perennial grasses are outcompeted by faster growing exotic annual grasses (Clausnitzer et al., 1999; Vasquez et al., 2008).

To revegetate or restore exotic annual grass-invaded rangelands, exotic annuals must be controlled to allow perennial grass seedlings to establish. Exotic annual grass can be effectively controlled with preemergent herbicides (Monaco et al., 2005; Kyser et al., 2007, 2013). Imazapic is a common preemergent herbicide used to control exotic annual grasses in the sagebrush ecosystem (Sheley et al., 2007; Davies and Sheley, 2011; Kyser et al., 2013). Seeding of perennial vegetation is often postponed for 1 yr after imazapic application to limit nontarget herbicide damage to seeded species. However, control of exotic annual grasses is finite as they quickly redominate the site if resources are not used by perennial vegetation (Davies, 2010; Sheley et al., 2012; Davies et al., 2015). Logically, it would be advantageous to seed perennial vegetation at the same time as imazapic application to give perennial vegetation a longer window to establish before experiencing significant pressure from exotic annuals. Efforts to establish perennial vegetation from seed at the same time as imazapic application have produced variable results, with success generally being limited likely due to imazapic-induced mortality of seeded species (Sheley et al., 2012; Davies et al., 2014).

In this situation, herbicide toxicity is prospectively a limitation to seedling establishment. Seed enhancement technologies designed to overcome this specific barrier to seedling establishment would likely improve revegetation success. Activated carbon can be used to deactivate herbicides as it has a high adsorption capacity for many organic compounds, including many herbicides, because of high surface area per unit volume and a system of submicroscopic pores (Bovey and Miller, 1969; Coffey and Warren, 1969). In row crops, activated carbon has been applied in a band as a slurry over seeded rows to protect the crop from the herbicide (Lee, 1973). Applying activated carbon as a band does not allow for full control of weeds as weeds within the band are protected from the herbicide (Lee, 1973). Alternatively, applying activated carbon as a seed coat has been proposed to protect seeded species from herbicides (Hagon, 1977; Scott, 1989). Seed coating, in contrast to banding, provides herbicide protection only to the seed and a relatively thin layer around the seed. This thin layer of activated carbon may not prevent herbicide uptake by the seeded species as the radical extends into the soil where the herbicide is still active (Madsen et al., 2014).

Activated carbon herbicide protection pods (HPPs) may be an ideal medium between banding and seed coating (Madsen et al., 2014). Activated carbon is incorporated into a dough mixture containing seeds, water-sensitive binders, and other additives and then extruded through a rectangular die. The extruded dough mixture is then cut into strips and dried (for more details see Madsen et al., 2014). In a pot study in a grow room, HPPs protected a seeded perennial grass from imazapic at all applications rates (70 – 210 g acid equivalent · ha^{-1}) (Madsen et al., 2014). Thus, this seed-enhancement technology has potential applicability for revegetation of exotic annual grass – invaded rangelands but needs to be field tested.

The objective of this study was to determine if HPPs could protect a commonly seeded bunchgrass, crested wheatgrass (*Agropyron desertorum* [Fisch.] Schult.), from imazapic applied to control exotic annual grasses. We evaluated using HPPs with a simultaneous imazapic application on a cheatgrass-dominated site and another site dominated by medusahead. We expected that 1) exotic annual grasses would be controlled with the imazapic application and 2) seeded bunchgrass abundance would be greater when seeded as HPPs compared with bare seeded.

Methods

Study Sites

The study was conducted in southeast Oregon at two study sites that were formerly Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & A. Young)—bunchgrass plant communities. Climate is characteristic of the northern Great Basin with cool wet winters and hot dry summers. Both sites were invaded by exotic annual grasses, and perennial vegetation was limited, though native perennial bunchgrasses and forbs were more abundant on Site 2 than Site 1. Site 1 was 67 km southeast of Burns, Oregon at 1045 m above sea level. This site was relatively flat (<2% slope) with clay loam soil. The ecological site is SR Clayey 9 – 12 PZ (R010XC021OR). Long-term (1981 – 2010) average annual precipitation was 267 mm. Crop-year (1 October to 30 September) precipitation was 274 mm (104% of long-term average). Medusahead was the dominant vegetation at Site 1. Site 2 was 7 km north of Burns, Oregon at 1288 m above sea level. This site was on a south aspect with 30% slope with loam soil. The ecological site is South Slopes 10 – 12 (R023XY300OR). Long-term (1981 – 2010) average annual precipitation was 306 mm. Crop-year precipitation was 277 mm (90% of long-term average). Cheatgrass was the dominant vegetation at Site 2. Both sites were fenced to exclude livestock during the experiment.

Experimental Design and Measurement

This study was implemented at two sites, and at each site treatments were arranged in a randomized block design and replicated four times. Treatments were 1) HPPs and imazapic application (HPPs), 2) bare seed and imazapic application (bare seed), and 3) untreated and unseeded control (control). Treatments were randomly assigned to 1 × 3 m plots with a 1-m buffer between plots. Both seeded treatments (HPPs and bare seed) were seeded with crested wheatgrass at 400 $\text{PLS}\cdot\text{m}^{-2}$ using a Kincaid Push Planter (Kincaid Equipment Manufacturing, Haven, Kansas). Drill rows were 3 m long running parallel to the long edge of the plot and spaced at 25, 50, and 75 cm on the short edge of the plot. Pure live seed was 75% and determined using the petri dish germination method. The formulation for the HPPs by dry weight was 34% activated carbon, 42% Ca Bentonite, 4% worm castings, 12% compost, 4% super absorbent powder, 1.6% super absorbent fine granules, and 2.4% seed. Each HPPs contained on average 8 PLS of crested wheatgrass. Dry materials were thoroughly mixed, and then liquid Selvol-205 prepared with a 1% solid content was incorporated to create a dough. Dough material was pushed through an extruder (Model 468, Lem Products, West Chester, OH) with an 8 × 16 mm die. Extruded dough was cut into 16-mm lengths, resulting in 8 × 16 × 16 mm pods. On 22 September 2015, immediately after seeding the HPPs and bare seed, imazapic (Panoramic 2SL, Alligare, Opelika, AL) was applied at a rate of 87.5 g $\text{ai}\cdot\text{ha}^{-1}$ with a handheld CO_2 sprayer (R&D Sprayers, Opelousas, LA) with a tank pressure of 206.8 kPa. During imazapic application, temperatures were 19°C and 31°C, relative humidity percentages were 27% and 17%, and average wind speeds were 2 and 7 $\text{km}\cdot\text{hr}^{-1}$ at Sites 1 and 2, respectively.

Density of crested wheatgrass seedlings was determined by counting all seedlings in drill rows in March (early) and June (late) of 2016. Leaf density, plant height, leaf length, and leaves per seedling were only sampled in March due to sampling error in June. Herbaceous vegetation density was measured in June using ten 0.2-m^2 quadrats. The 0.2-m^2 quadrats were placed evenly along two transects that were placed at the 25 and 75 cm locations on the short edge of the plot and paralleled the long edge of the plot. Density for perennial vegetation was measured by species by counting all individuals rooted in the 0.2-m^2 quadrats. Density of annuals was determined by counting by species all individuals rooted in the 10% segment of the 0.2-m^2 quadrats.

Statistical Analyses

We used repeated measures analysis of variance (ANOVA) using the PROC MIX method in SAS v. 9.4 (SAS Institute, Cary, NC) to evaluate seedling density response to treatments. The appropriate covariance structure, compound symmetry, was selecting using Akaike's Information

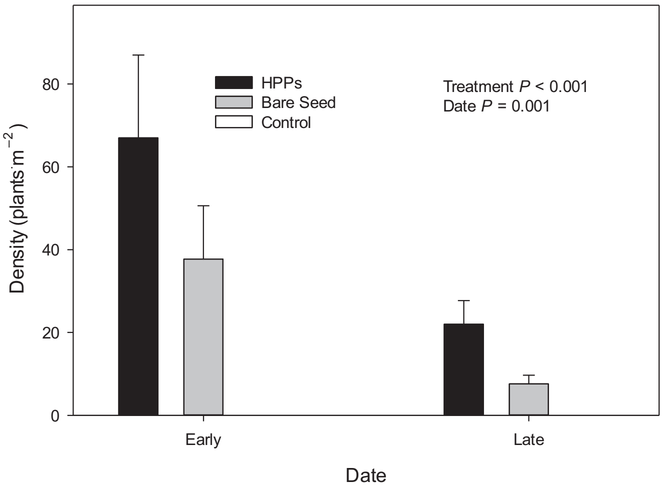

Figure 1. Density (mean + S.E.) of crested wheatgrass seedlings in treatments in March (Early) and June (Late). HPPs indicates seeds seeded in activated carbon pod followed by imazapic application; Bare Seed, bare seeds seeded followed by imazapic application; and Control, untreated and unseeded control.

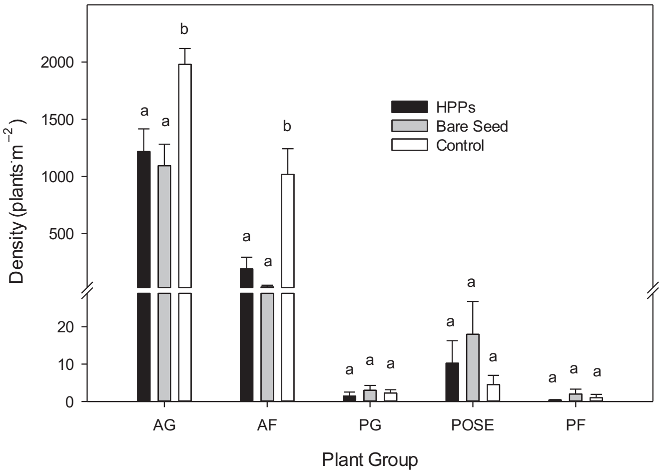

Figure 2. Density (mean + S.E.) of plant groups in treatments in June. HPPs indicates seeds seeded in activated carbon pod followed by imazapic application; Bare Seed, bare seeds seeded followed by imazapic application; Control, untreated and unseeded control; AG, exotic annual grasses; AF, annual forbs; PG, large perennial grasses (excluding crested wheatgrass); POSE, Sandberg bluegrass; and PF, perennial forbs. Different letters indicate difference among treatment means within plant groups ($P \leq 0.05$).

Criterion (Littell et al., 1996). Sampling date was the repeated variable, treatment was considered a fixed variable, and site, replication, and interactions were considered random. For all other analyses, we used ANOVA using the PROC MIX method in SAS v. 9.4. Significance was set at $\alpha \leq 0.05$. Treatment means were separated using LSMEANS method in SAS v. 9.4 ($P \leq 0.05$). Means were reported with standard errors in the text and figures. Herbaceous vegetation was grouped into six groups for analyses: crested wheatgrass, large perennial grass, Sandberg bluegrass (*Poa secunda* J. Presl), perennial forbs, exotic annual grasses, and annual forbs. Crested wheatgrass was analyzed individually because it was the seeded species. Sandberg bluegrass was also analyzed separately because it responds differently to disturbances, is smaller in stature, and phenologically develops earlier than other perennial grasses in this ecosystem. The exotic annual grass group was composed of cheatgrass and medusahead.

Results

Density of crested wheatgrass seedlings varied by treatment ($P < 0.001$), date ($P = 0.001$), site ($P < 0.001$), and the interaction between treatment and date ($P = 0.043$). Crested wheatgrass density was greatest in the HPPs, followed by the bare seed, and then the control treatment (Fig. 1**;** $P < 0.001$). At the late sampling date, crested wheatgrass seedling density was 3-fold greater in the HPPs compared with the bare seed treatment. Crested wheatgrass density was greater in the early sampling compared with the late sampling in the HPPs and bare seed treatment but remained the same in the control treatment (0.0 ± 0.0 plants·m^{-2}). Averaged across treatments and dates, crested wheatgrass density was 6-fold greater on Site 1 (38.8 ± 9.2 plants·m^{-2}) compared with Site 2 (6.1 ± 1.4 plants·m^{-2}). Density of crested wheatgrass leaves varied by treatment ($P < 0.001$) and site ($P < 0.001$). The HPPs treatment (302 ± 70 leaves·m^{-2}) had approximately double the density of crested wheatgrass leaves compared with the bare seed treatment (165 ± 52 leaves·m^{-2}) in March ($P = 0.011$). Crested wheatgrass leaf density was greater in the HPPs and bare seed treatment compared with the control (0.0 ± 0.0) ($P < 0.001$ and $= 0.003$). Leaf density was fivefold greater at Site 1 compared with Site 2. Crested wheatgrass average and maximum height, average and maximum leaf length, and average and maximum number of leaves per seedling did not differ between the HPPs and bare seed treatment in March ($P > 0.05$).

Annual grass density differed among treatments (Fig. 2**;** $P = 0.004$) but not sites ($P = 0.151$). Annual grass density in treatments where imazapic was applied (HPPs and bare seed treatments) was about half of the untreated control ($P = 0.006$ and 0.002, respectively). Density of annual grass did not differ between the HPPs and bare seed treatments ($P = 0.617$). Annual forb density varied among treatments (see Fig. 2; $P < 0.001$) but was similar between sites ($P = 0.312$). Annual forb density was 5- and 30-fold greater in the untreated control compared with the HPPs and bare seed treatments ($P = 0.001$ and < 0.001). Annual forb density did not differ between the HPPs and bare seed treatment ($P = 0.474$). Large perennial grass (excluding crested wheatgrass) and Sandberg bluegrass density did not vary among treatments (see Fig. 2; $P = 0.443$ and 0.132) but differed between sites ($P = 0.020$ and < 0.001). Large perennial grass density was five times greater on Site 2 (3.8 ± 1.0 plants·m^{-2}) compared with Site 1 (0.8 ± 0.5 plants·m^{-2}). Sandberg bluegrass density was greater at Site 2 (21.8 ± 6.0 plants·m^{-2}) compared with Site 1 (0.3 ± 0.2 plants·m^{-2}). Perennial forb density did not vary among treatments ($P = 0.300$) but did differ between sites ($P = 0.047$). Density of perennial forbs was 10 times greater at Site 2 (2.1 ± 1.0 plants·m^{-2}) compared with Site 1 (0.2 ± 0.1 plants·m^{-2}).

Discussion

Herbicide protection pods (Madsen et al., 2014) can be used to decrease herbicide effects on seeded species when imazapic is applied to control exotic annuals in sagebrush rangelands. In this study, crested wheatgrass seedling density was 300% greater at the end of the study when seeded in HPPs compared with seeded as bare seed when exotic annual grasses were simultaneously being controlled with imazapic. Our results suggest that HPPs may be effective in medusahead- and cheatgrass-invaded rangelands with different site, climate, and vegetation characteristics.

We expect that the benefits of HPPs over bare seed are primarily the result of activated carbon deactivating the preemergent herbicide around seeds. However, agglomerated seeds can improve seedling performance compared with seeds planted individually (Madsen et al., 2012). Activated carbon may also increase plant growth by increasing nutrient availability (Lau et al., 2008) and limiting allopathy (Cipollini, 2002; Kulmatiski and Beard, 2005; Cipollini et al., 2008). Thus, some of the differences between HPPs and bare seed may be partially attributed to factors other than the deactivation of imazapic.

We anticipate that the advantage of using HPPs may have been even greater at higher application rates of imazapic. Madsen et al. (2014) found that HPPs were effective at limiting imazapic damage to a seeded bunchgrass even at the highest rate applied (210 g ae $\cdot$ ha^{-1}). In our study, exotic annual grasses (and annual forbs) were reduced with our lower rate of imazapic application, but control of exotic annual grasses was approximately 50%. A higher application rate of imazapic would have likely increased the control of exotic annual grasses (Sheley et al., 2007) and also damage to seeded perennial grasses that were not incorporated in HPPs. However, we speculate, based on prior research (Madsen et al., 2014), that perennial grass seeded in HPPs would have continued to be protected at high imazapic application rates. With better control of exotic annual grasses, perennial grasses seeded in HPPs would likely have a more favorable environment for establishment and growth because of reduced competition. Successful revegetation of exotic annual grass — invaded rangelands requires effective control of exotics to allow seeded perennial vegetation time to establish and grow large enough to limit redomination by annual grasses (Davies, 2010; Nafus and Davies, 2014). Therefore, greater control of exotic annual grasses was probably needed, which would decrease seeded bunchgrass abundance in the bare seed treatment as a result of higher herbicide application rate, likely resulting in even greater difference between the HPPs and bare seed treatment.

Our results suggest that HPPs could be used in a single-entry system to seed desirable species at the same time imazapic is applied to control exotic annuals. Revegetation of exotic annual grasslands traditionally require two entries: application of preemergent herbicide and seeding 1 yr later to reduce herbicide damage to seeded species (Davies, 2010; Davies et al., 2014, 2015). A single-entry system where herbicide and seeding occur simultaneously would reduce cost and logistical challenges (Sheley et al., 2012). Similar to Sheley et al. (2012), our results with the bare seed treatment suggest that, at less than desired levels of annual grass control with imazapic, a single-entry system can establish some perennial bunchgrasses in exotic annual grasslands. However, greater control of exotic annuals is likely needed to shift dominance from annuals to perennials. Successful revegetation of exotic annual grass — invaded rangeland requires good control of exotic annuals and high establishment of perennial vegetation (Young and Clements, 2000; Kyser et al., 2007; Davies et al., 2014; Nafus and Davies, 2014). Low rates of imazapic may not provide adequate control of exotic annuals. Ideal imazapic application rates for controlling annual grass can vary by soils, weather, litter, application methods and timing, and other factors (Monaco et al., 2005; Kyser et al., 2007; Nafus and Davies, 2014). A single-entry system will probably be more successful with HPPs that likely allow land practitioners the ability to apply higher rates of imazapic for better and more consistent control of exotic annuals without damaging seeded bunchgrasses (Madsen et al., 2014).

The use of HPPs to allow perennial bunchgrasses to be seeded simultaneously with exotic annual grass control may improve revegetation success by allowing seeded species the ability to establish when exotic annual grass competition is most reduced. This is important because seedlings of perennial grasses are not very competitive with faster growing exotic annual grasses (Clausnitzer et al., 1999; Vasquez et al., 2008). The larger and more established perennial bunchgrasses are before experiencing significant pressure from exotic annuals, the more likely revegetation will be successful. Simultaneously seeding vegetation with exotic annual grass control with an imazapic application would also allow seeded species 1 more yr of growth while exotic annual competition is reduced compared with the traditional approach. Once perennial bunchgrasses are established, they can be quite competitive with exotic annuals and are critical to limiting exotic annual grasses in the sagebrush ecosystem (Chambers et al., 2007; Davies, 2008; James et al., 2008).

Crucial to the applicability of using HPPs to revegetate exotic annual grass — invaded sagebrush rangelands, we found that this approach worked at two sites differing in soil characteristics, vegetation, and climatic conditions. We did detect differences in crested wheatgrass abundance between sites, which is likely caused by differences in residual perennial vegetation abundance. Site 1 compared with Site 2 had lower abundance of large perennial grasses, Sandberg bluegrass, and perennial forbs, resulting in less competition and likely the 600% greater abundance of crested wheatgrass seedlings. However, at both sites the HPP treatment markedly increased crested wheatgrass seedling abundance compared with the bare seed treatment. Clearly, this approach needs to be tested at additional sites under various weather conditions; however, it should be noted that this approach worked on both medusahead- and cheatgrass-invaded rangelands. Further research evaluating the effectiveness of HPPs with various restoration species and at higher rates of imazapic applied to better control exotic annual grasses would also be valuable.

Implications

Seed enhancements that overcome barriers to the establishment of seeded species are critically needed, especially in annual grass — invaded rangelands. Activated carbon applied as HPPs appears to overcome the barrier of imazapic toxicity to seeded species. Thus, HPPs can be used to seed desired species simultaneously with the application of imazapic to control exotic annual grasses. This will provide a longer interval for seeded species to establish before experiencing significant pressure from exotic annuals and likely increase the probability that seeded species will be large enough to successfully compete with exotic annuals. This may increase the likelihood of establishing a perennial-dominated community capable of limiting exotic annual grasses. The use of HPPs also allows for a single-entry approach, which may reduce cost and logistical challenges compared with the traditional multi-entry approach. Though HPPs have clear potential to improve revegetation and restoration of exotic annual grass — invaded rangelands, they are currently not commercially available. Further refinement and evaluation of the potential of HPPs to be used for revegetation and restoration, as well as subsequent demand by restoration practitioners, will probably determine if HHPs will become a commercially available seed enhancement technology.

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