Reforestation in the Appalachian coalfields has primarily relied on the planting of nursery stock late in the dormant season. This study examined the use of direct seeding during the fall, a practice that, if successful, could both reduce costs of planting and open up a new season for reforestation planting. Black walnut is of particular value for wildlife habitats, timber value, and even human nutrition. In addition, it normally occurs in diverse forests with rich soils of the region. Therefore, establishment on previously surface-mined lands may indicate a positive successional trajectory and resilience.

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they undergo reclamation to forestry post-mining land use, termed the Forestry Reclamation Approach (FRA) [5].

In addition to currently mined lands, there are also so-called “legacy” surface mines, where reclamation required by the coal operator has been completed, but was done in a way that is not compatible with the succession to forest or the success of trees that have been planted. These legacy mine lands are estimated to cover 600,000 hectares in the Appalachian region [6], and represent a large potential for restoration to forest in the United States. These forests can be of economic and ecological value to the region, which is increasingly important as the coal resources that have provided economic benefits in the past have been removed [7]. In addition, these lands represent a significant area that used to serve as carbon storage (both as coal and forest), but which is now unable to serve that role [8]. Therefore, it is in the interest of not only the Appalachian coal region and the United States, but also the world as a whole, to find ways to restore forest on these legacy mine sites.

Much forestry reclamation research and practice has relied on the planting of nursery stock seedlings, typically in the late part of the dormant season or very early growing season (Feb–Apr). Fall/early dormant season plantings have generally been avoided, due to the concern that nursery seedlings planted then will not be able to successfully overwinter (due to the short time they would have to establish roots, etc.). Early spring has also been considered the best time to direct seed [9], although fall seeding is acceptable under certain conditions [9], with screening from rodents advised [10]. In addition, because vegetative competition on legacy sites typically presents a major barrier to the establishment and growth of native trees [11], planting by seed may disadvantage planted trees in their struggle against groundcover vegetation. The concentration of planting efforts in the early spring results in a very busy few months of planting, with the number of trees planted/hectares restored being limited in part by this factor. If the fall/early dormant season could be used successfully, it would open up an additional planting window for the region. In addition, if seeds can be successfully planted at this time (rather than nursery stock seedlings), it may reduce the cost (and eliminate loss associated with overwintering nursery stock planted). Therefore, the type of planting (seed vs. nursery seedling) is a factor in the restoration of these systems that deserves some attention.

Studies examining the use of direct seeding on surface mine sites are somewhat limited, but there have been some examining the reestablishment of American Chestnut (Castanea dentata (Marsh.) Borkh.) in eastern forests from seed. Some of these have also examined the effect of tree shelter use. French et al. [12] found a higher survival rate for direct-seeded plants and fewer indicators of stress compared to transplanted seedlings. Barton et al. [13] found much greater germination for direct-seeded chestnuts when a tree shelter was used (attributed to shelters protecting seeds from consumption by small mammals). McCarthy et al. [14] found that the presence of a tree shelter greatly improved the survival of chestnuts planted as seed (and the authors observed herbivory damage both directly after planting and for seedlings that emerged). In general, these authors have concluded that herbivory pressure can be quite high, and thus tree shelters are needed. However, Skousen et al. [15] found no difference for planted chestnut seeds with and without shelters, and Ponder [16] found that the effect of tree shelters varied for the four different species he looked at, which were planted as seedlings. Therefore, the need for tree shelters in mineland reforestation is not entirely clear.

Eastern black walnut (Juglans nigra L.; hereafter referred to as black walnut) is a tree native to all of the Appalachian coal region and has a number of unique properties. It is a high-value veneer quality timber and is also valuable as a wildlife and human food. In addition, it is commonly used in agroforestry (e.g., [17,18]) and conservation planting [19]. Black walnut has a unique chemistry, exuding a compound called juglone, which has been clearly linked to allelopathic properties (e.g., [20,21]), and which might serve as a natural deterrent to herbivores. Because it is widespread and easily identified (there are no common trees which produce a similar nut throughout the region; butternut or white walnut Juglans cinerea L. is quite rare), the nuts are readily available in many different locations. Black walnut can be found as specimen trees in urban/suburban areas, and they establish and spread readily in favorable soils (such as in old fields, fence rows, etc.). In addition, black walnut has been
successfully used in reforestation planting on surface mines and is included in the list of recommended species [22,23].

Although included in recommendations, the results with black walnut in reforestations on mine sites are somewhat mixed. Two early studies that included direct-seeded black walnuts had conflicting results. Schavilje [24] reported good first year germination and survival, but Linstrom [25] recorded only 15% survival of black walnut after six years, although later trials resulted in ranges in survival between 6% and 82% (reported in [9]). Vogel [22] reported that black walnut had been well-established from both seed and seedlings and performed best in Indiana, Illinois, and Missouri on moist ungraded minesoils with a pH of 6.0–7.5, but that survival and growth were poor on Appalachian minesoils (likely due to the lower pH). A study by Chaney et al. [26] looked at the performance of black walnut and northern red oak (*Quercus rubra* L.) twelve years after planting on a site in Indiana and found that the growth of black walnut met the requirements of the forestry post-mining land use when competing groundcover was controlled. These trees were planted as 1-0 seedlings and the A and B soil horizons were also stockpiled and spread out prior to planting [26]. Burger and Fannon [27] found that black walnut (planted as 2-0 nursery seedlings and not protected with shelters) grew the slowest of the seven hardwood species they looked at after 15 years’ growth on a site in southwestern Virginia, but its survival (at 60%) was comparable to red and white oak. In another study that looked at 31 years of growth from reforestation in Ohio, the authors found a 60% loss in black walnut seedlings planted [28]. Black walnut was included in a mix of six hardwood species direct-seeded on 10 sites across three states and after five years of growth, performed similarly to Black cherry, Northern red oak, Sugar maple, and White oak, but the survival of these hardwoods was relatively low at 23–48% (with black walnut survival at 27%) [29]. Black walnut (planted as nursery stock) also responded similarly to differences in compaction as most of the other species included in a Kentucky study, with 68% survival after eight years in loose-dumped spoil [30]. Overall, these results suggest that black walnut is a suitable native forest species to include in planting on surface mine sites, although it is unclear whether planting by seed may be an effective option and whether tree shelters can enhance reforestation success.

This study aimed to examine differences in growth for black walnut as affected by planting type (seed or 1-0 nursery seedling) and the presence of a tree shelter (yes or no) at a site in eastern Kentucky, USA. The initial planting was done in November to examine the use of a late fall/early dormant season window, and measurements were made in the first, second, and fifth growing seasons.

2. Materials and Methods

Walnuts (husk and nut) were collected mid-Sept to mid-Oct 2011 in and around Berea, Kentucky. Husks were separated from the nuts by either driving over material with a vehicle (for green husks) followed by hand separation, or by hand separation if the husk was blackened. Nuts were then washed and placed in a tub of water to screen for viability. The nuts that floated were discarded [10], while the nuts that sank were stored in moist peat moss in refrigeration until being planted on November 5, 2011.

The site for this study was a reclaimed mine site at the Fishtrap Wildlife Management Area in Pike County, KY (37.382583, −82.340331). This site was actively mined from 1996 to 2000. The plots were located in an area reclaimed as Fish and Wildlife habitat (one of several post-mining land use alternatives containing approximately 75% grassland and 25% tree/shrubland). The experimental design consisted of four combinations (full factorial) of each of the two main treatment types: planted by seed or one-year nursery stock, and either with a tree shelter or without a tree shelter. Each plot was 17 m × 9 m, with three replicate plots per treatment combination (Figure 1). The plots were ripped within two months of the planting date according to FRA standards [31]. The seedlings and nuts were planted with 1.5 × 1.5 m spacing (50 nuts or seedlings per plot). All the nuts and seedlings received one N-P-K planting tablet (20-10-5) at planting. Shelters were 119 cm tall and 9 cm in diameter, and were made by Tubex (South Wales, UK). Each tree was individually tagged at the first measurement in 2012.
To evaluate the survival effectiveness of the main treatments on survival in all years (Table 1) is indicative of shelter having no significant benefit for the seedlings, but having a negative impact on those from seed (Figure 2A). Measurements were made in May 2012 (six months after planting, first growing season), May 2013 (1.5 years after planting, second growing season), and May 2016 (4.5 years after planting, fifth growing season). Measurements for each seedling included the height (cm) and stem diameter (mm). The tree volume index was calculated as diameter² × height (this has been used as a composite measurement for young trees, ex. [32]). The results are reported for each sampling period.

Differences in tree height, diameter, and volume index were detected by linear mixed models, using PROC MIXED (SAS 9.4, SAS Institute Inc., Cary, NC, USA), with treatments (shelter, planting method) and their interaction modeled as fixed effects and individual trees within a block modeled as random effects. Data for every tree measurement was included for all years (missing or dead trees were excluded). To evaluate the survival effects, the proportion of planted individuals still alive in each year was calculated for each plot. Differences in survival proportions were detected by linear mixed models, using PROC GLIMMIX (SAS 9.4), with treatments (shelter, planting method) and their interaction modeled as fixed effects and blocks modeled as random effects (with a default error term). Significant ANOVA results (p < 0.05) were followed up with pairwise comparisons using Tukey’s tests.

Figure 1. Plot layout of the research site. Each treatment combination had three replicate plots, and each plot contained 50 seedlings or seeds.

We hypothesized that trees planted as seedlings and those utilizing shelters would result in greater growth and survival in all the measured response variables: height, diameter, tree volume, and survival rate.

3. Results

3.1. Survival

Survival was significantly affected by shelter presence, planting type, and their interaction for the first growing season (Table 1). There was higher survival for seedlings compared to those from seed (98% vs. 52% for 2012, 83% vs. 61% in 2013, and 84% vs. 61% in 2016, respectively), although by the second and fifth growing seasons, unsheltered trees planted as seeds exhibited similar survival to seedlings (Figure 2A). Survival for those from seed that were sheltered remained significantly lower than the other three treatments throughout the study (Figure 2A). The significant interaction of the two main treatments on survival in all years (Table 1) is indicative of shelter having no significant benefit for the seedlings, but having a negative impact on those from seed (Figure 2A).
Table 1. P-values for the main treatment effects and their effect on measured response variables. P-values > 0.05 are indicated as nonsignificant (NS).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Treatment Effect</th>
<th>2012</th>
<th>2013</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survival</td>
<td>Shelter</td>
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<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Planting Type</td>
<td>&lt;0.0001</td>
<td>0.0009</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>Shelter × Planting Type</td>
<td>0.0244</td>
<td>0.0062</td>
<td>0.0160</td>
</tr>
<tr>
<td>Height</td>
<td>Shelter</td>
<td>0.0007</td>
<td>&lt;0.0001</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Planting Type</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Shelter × Planting Type</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Diameter</td>
<td>Shelter</td>
<td>0.0318</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Planting Type</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Shelter × Planting Type</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Volume</td>
<td>Shelter</td>
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<td>0.0013</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Planting Type</td>
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<td>Shelter × Planting Type</td>
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<td>NS</td>
</tr>
</tbody>
</table>

Figure 2. Means (+SE) for (A) survival; (B) height; (C) diameter; and (D) volume, as measured in the first (2012), second (2013), and fifth (2016) growing seasons. Lowercase letters indicate a significant difference between treatment means within each year.

3.2. Height

Height was significantly affected by shelter presence and planting type in 2012 and 2013, but by 2016, it was no longer significant (Table 1). In the first two growing seasons, shelter presence had a positive impact on height for both planting types, but by the fifth growing season, all four treatment combinations were comparable (Figure 2B).
3.3. Diameter

The diameter results were quite similar to the height in terms of treatment effects. In the first growing season, both of the main treatment effects were significant, but by the second growing season, only planting type (seedling > seed) was significant (Table 1), while the effect of shelters was no longer significant (Figure 2C).

3.4. Volume

The volume measurement combines height and diameter measurements to get an idea about the overall size of young seedlings. For this measurement, the two main treatment effects, as well as their interaction, were significant in the first and second growing seasons, but none were significant by the fifth (Table 1). As with diameter and height, by the fifth growing season, there was no difference between treatments (Figure 2D).

4. Discussion

Throughout the study, survival with the sheltered seed treatment was significantly lower than the other treatments. During the first growing season, there was nothing to measure for many of these trees in the sheltered seed treatment as many appeared to have not germinated. We dug a bit into the ground inside the shelters for a few of these to try to figure out if the seeds were still there or had been removed by herbivores, and found that the seeds were present, but had begun to rot and easily broke apart. Prior to this first measurement, it had been a very wet winter, and it seemed that moisture was trapped in the shelters. It is known that tree shelters modify the microclimate, and in particular, increase water condensation [33]. In this case, we believe it was not only water condensation, but also precipitation, during a wet dormant period after planting that was also higher within the shelters and caused the seeds to deteriorate. It is also worth noting that soil compaction is a problem that plagues legacy mine sites [34], and that although ripping was done, drainage may still have been limited in some areas. In a drier dormant period, and/or on better drained soils, we may not have seen such high losses of sheltered seeds during the dormant period, although it is worth noting that precipitation has been increasing primarily in winter and spring in this region [35]. The apparent increase in survival (from 2012 to 2013 for both seed treatments, and from 2013 to 2016 for the unsheltered seedling treatment) is common in mine reforestation studies. Seedlings frequently experience significant dieback in the first years after planting and can appear dead, but subsequently respout and be recorded as living in later surveys. In addition, seeds sometimes fail to germinate immediately, leading to an underestimation of germination rates in initial surveys. In our case, there were a small number of seeds that germinated either late in the first year (after measurement) or early in the second year, as the mean survival was slightly higher in 2013 compared to 2012 (although not significant). The USDA Forest Service [10] has reported that “Properly stratified seeds usually germinate within 4 weeks, but much variation among seed lots can be expected” (p.457).

Survival of our trees in the fifth growing season ranged from 82% to 86% for the nursery stock, and 50% to 72% for the seed. Fields-Johnson et al. [36] reported 76% survival of chestnuts planted as seed with shelters in the first growing season (they did not have any nuts without shelters), and Barton et al. [13] found similar survival (70%) for Chinese chestnuts from seed with shelters in their fifth growing season. Therefore, our survival numbers for walnut seeds without shelter are comparable to those that have been found for chestnuts from seed with shelters planted on surface mine sites. Outside of surface-mined lands, Bendfelt et al. [17] looked at bare-root black walnut seedlings in an agroforestry setting with and without the same kind of shelters we used (as well as a shorter poultry wire shelter) in Virginia, USA, and found no shelter effect as survival was near 100% in all treatments for the first three growing seasons included in the study.

For all of the other three measurements (height, diameter, and volume), treatment effects that were significant in the first two growing seasons had disappeared by the fifth. This highlights the
importance of following reforestation plantings beyond the first two growing seasons, as trends that appear during that time may not remain significant. (It is worth noting that although not significant, the sheltered seed treatment did have diameter and volume means that were still markedly below the other three.) It is also interesting to note that the height of sheltered seedlings was actually lower in 2016 than in 2013. This seems to be due to a number of those seedlings experiencing quite a bit of dieback (which was noted at the time of data collection). There were also a couple that were resprouts from the rootstock. None of the other treatments appeared to experience the same degree of dieback. Ponder [37] noted that although 120 cm tree shelters resulted in significant increases in height for black walnut seedlings in a study in Missouri, USA, they also delayed hardening off, which led to significant dieback at one of his three sites. Hemery and Savill [38] noted a similar problem with *Juglans regia* L. in England (they compared 120 cm, 75 cm, and no shelter). They noted that the tallest shelters seemed to promote rapid stem growth, but that growth was more susceptible to dieback, so annual gains were much lower than for the 75 cm shelters. In addition to this potential impact on growth, we did note in our study that a number of shelters were leaning or completely laying on their sides at our site, starting in December 2012 (when the site was revisited after the first measurement). This site experienced strong storms, which the 120 cm shelters were susceptible to. This problem has been noted by others [39]. For this reason, if using the tall tree shelters, we recommend monitoring as frequently as possible (and restaking as necessary).

Herbivory was definitely present at our site, but did not seem to be so strong as to prevent unsheltered trees from being able to establish and grow. Black walnut’s unique chemistry may provide some deterrence to herbivory, although that remains unclear. In a study on deer browsing in Connecticut, USA, Ward and Stephens [40] found that the height of black walnut was lower after three years of growth (than at planting) for those seedlings without shelters due to heavy browsing. Bendfelt et al. [17] noted that in their study with black walnut and honeylocust (*Gleditsia triacanthos* L.) in Virginia, deer tended to rub rather than browse the black walnut (whereas they browsed honeylocust). USFS [41] says of black walnut, “Deer browse on buds and rub antlers against young trees. Mice and rabbits gnaw on the stems of young trees during the winter, and squirrels dig up and eat direct-seeded nuts and feed on green and mature nuts still on the trees” (p.397). Farlee [42] recommends protection if black walnuts are to be planted within 300 feet of woodlands or other habitats favorable for squirrels and other small mammals. Therefore, it seems most likely that the susceptibility of black walnut to herbivory/seed predation is determined by the severity of herbivore pressure and perhaps the presence of other browse material.

From an economic standpoint, the collection of seed and planting either as seed or seedlings requires a similar time and economic commitment. However, directly seeding walnuts will produce a cost saving by not having to plant, care for, and lift seedlings from nursery beds, which generally requires a one to two year commitment. Alternatively, if material is to be purchased directly, the cost of the seedlings (which varies widely, but for direct bare-root seedlings, ranged from $0.10 to $0.75 USD each in 2019, C. Barton personal communication) is most certainly higher than it would be for seed. As mentioned previously, black walnut is a very widespread tree throughout the U.S. [41] and is a common tree, making the collection of seeds quite simple (note that, if possible, the collection of seeds should be close to the planting site as regional variation in climatic adaptation has been observed [43]). Grossnickle and Ivetić [44] have provided a thorough discussion of the advantages and disadvantages of using seeds vs. nursery stock in reforestation. Tree shelters are an additional cost in both resources and time, with the Tubex tree shelters alone (without stakes) costing around $5.00 USD each (P. Angel personal communication). Therefore, the use of direct seeding without shelters represents a significant cost reduction compared to bare-root seedlings with shelters.

Given the similarity at five years for these four different treatments, it appears that black walnut can be successfully direct-seeded on this legacy mine site in the Appalachian region. It can also be successfully planted as nursery stock during the early dormant season, as was done in our study. In addition, shelters do not appear to be necessary for this species, and in fact, they may hinder
germination for those planted from seed. If a shelter is used, a shorter one (such as 70 cm) may be more beneficial than a taller one. More research is needed, but our results are promising for reforestation of this valuable species in the Appalachian region.

5. Conclusions

We found promising results for black walnut planted on a surface-mined site in Appalachia, USA. Of note was the success of direct-seeded seedlings without shelters, a practice that could reduce costs of reforestation planting. Considered more broadly, this study supports the use of black walnut in plantation or orchard-style plantings on mined land in Appalachia. The Appalachian region has long been dependent on the coal industry; as the coal industry has declined, the region has suffered from widespread economic depression. Forestry and forest-related industry represents an opportunity to diversify the regional economy, developing opportunities for job creation, land value improvement, and other economic development [7]. Black walnut is widely planted in long-rotation plantations, to be harvested as a high-value timber crop. Given its demonstrated suitability on mined land through five growing seasons in this study, this species may present a valuable economic opportunity for owners of Appalachian mined land. In addition to economic opportunity, improving tree growth on nonforested reclaimed mine land in Appalachia (so-called “legacy sites”) presents ecological opportunity—improving carbon sequestration in aboveground biomass, and providing food and habitat for wildlife.

Author Contributions: C.B. and P.A. conceived and designed the study and conducted the planting. S.H. and P.A. collected the data. K.S. analyzed the data. S.H. wrote the original paper draft, with significant contributions from all co-authors in the editing/revising process. We thank two anonymous reviewers for their feedback on the original draft.

Funding: This research was funded by the Berea College Undergraduate Research and Creative Projects Program.

Acknowledgments: Many Berea College undergraduate students helped to make this study possible. Brenda Richardson, former EDS faculty and her students were instrumental in collecting, processing, and planting black walnuts. Kaleigh Hire, Joshua Best, Reena Martin, and Joshua Reece all participated as undergraduate research assistants for one summer. We also thank two anonymous reviewers for their helpful feedback on the original manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

13. Barton, C.; Miller, J.; Sena, K.; Angel, P.; French, M. Evaluating the Use of Tree Shelters for Direct Seeding of Castanea on a Surface Mine in Appalachia. Forests 2015, 6, 3514–3527. [CrossRef]
18. Lehmkuhler, J.W.; Felton, E.E.D.; Schmidt, D.A.; Bader, K.J.; Garrett, H.E.; Kerley, M.S. Tree protection methods during the silvopastoral-system establishment in midwestern USA: Cattle performance and tree damage. Agrofor. Syst. 2003, 59, 35–42. [CrossRef]


44. Grossnickle, S.C.; Ivetić, V. Direct Seeding in Reforestation—A Field Performance Review. REFORESTA 2017, 4, 94–142. [CrossRef]