Tropical Dry Forest Restoration

Science and Practice of Direct Seeding in a Nutshell

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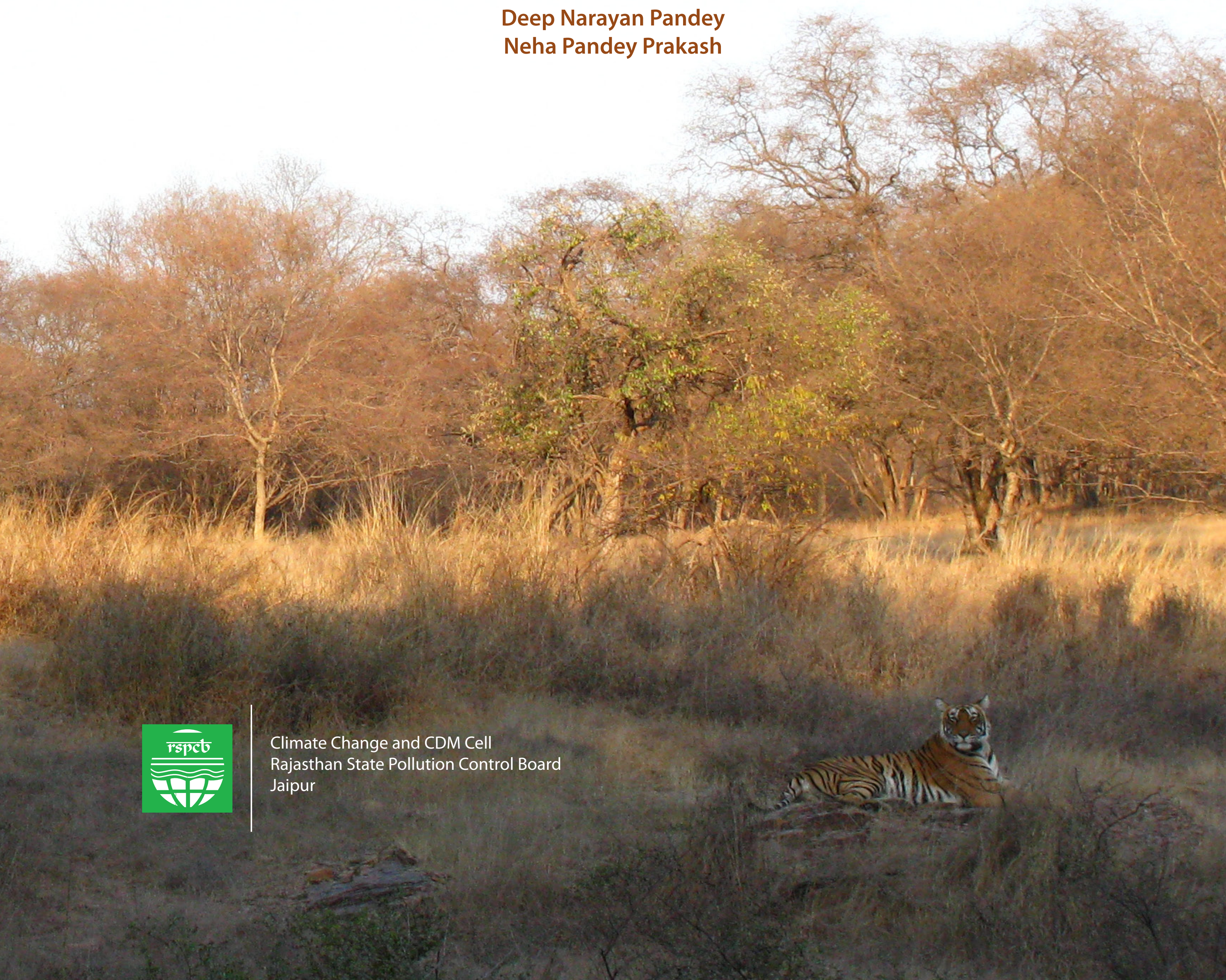

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1. Introduction

The continued deforestation and resultant large-scale degraded tropical lands pose urgency for restoration of biodiversity, ecological functioning, and improvement in the supply of goods and ecological services previously used by rural communities [1-10]. Experiential knowledge and scattered scientific evidence suggests that direct seeding is an efficient and cost-effective method for tropical dry forest restoration. However, few studies provide guidance on direct sowing of tropical dry forest (TDF) species in any detail. Indeed, insights that provide an integrated perspective derived from experiential, indigenous and scientific knowledge are practically lacking. Here we provide a practitioner's perspective and review the usefulness of direct seeding as a method for the tropical dry forest restoration. The core purpose is to bring in our experiential knowledge gained over the last three decades, weigh that in the light of cutting-edge peer-reviewed science, and arrive at an evidence-based solution that can be used by foresters and restoration managers. In other words, we attempt two things: testing the efficacy of our own experiential knowledge in the light of good science, and communicating coherent insights to field practitioners who can use this knowledge in making the difference on the ground (i.e., to bridge the gap in knowledge and action). To the best of our knowledge, this is the first comprehensive synthesis on restoration of tropical dry forests through direct seeding.

Direct seeding has been applied across a range of tropical forests [11-35]. Yet, even the most notable literature on tropical dry forests does not provide much guidance on direct seeding; See for example, [1, 7, 36-41]. Seeding can facilitate in overcoming the limitations of seed availability or absence of soil seed bank that potentially constrain the response of dry forests to rainfall [42].

Direct sowing is easier, simpler, and cheaper than planting seedlings. Utilizing direct sowing has economic and time-saving advantages, especially in inaccessible sites where establishing a nursery to produce and maintain plants can be avoided. It also reduces costs of transport and labor during soil preparation and sowing. Mechanical injuries and desiccation damage to seedlings can also be avoided.

Direct sowing also provides a large base for choice of species. Since it is not necessary to raise the seedling in the nursery, large number of species can be attempted, compared to planting. Raising of seedlings in the forest nursery requires large inputs in terms of time and money, that can be avoided by opting for the direct sowing. Direct sowing is also advantageous as it is comparatively easier to maintain the species mix during seeding than in plantations. Direct sowing can both be used as a stand-alone restoration method and can be combined with advance closure, assisted regeneration, and plantations. As direct sowing helps in enhancing biodiversity per unit area, it also helps in enriching of the plantations. It is much easier to develop multi-tier, multiple-species vegetation through direct sowing.

In this article, we first describe the major factors that are critically relevant for direct seeding in tropical dry forests (section 2). Next, we explore process and numerous aspects of implementation of direct seeding and provide a synthesis of science and our experience (section 3, table 1). We, then provide suggestions to overcome some challenges of seed and seedlings (section 4). Finally, we conclude with a future outlook (section 5).

2. Major factors relevant for direct sowing

2.1. Locality of the seed source: Many species in tropical dry forests have a wide range of geographical distribution, with genetically adapted characteristics to different environmental conditions found within their historic range. Populations of such species show differential provenance related germination, seedling growth, disease resistance, responses to frost and resilience to water and climatic fluctuations [43]. Thus, it is prudent to collect seeds locally or from the same geographic region so that advantage of context-specific local adaptation, developed in the long-term evolutionary period, is not lost [44].

2.2. Seed dormancy: The majority of dry tropical species possess orthodox seeds which are characterized by dormancy, and can be stored for longer duration. A few species also have recalcitrant seeds which possess little or no dormancy. Thus, seeds may require pre-treatment before sowing. For instance, seed coat dormancy can be overcome by mechanical or acid scarification or even by transit through animal guts [43]. Compared to tropical rain forests, of which about 62% species produce non-dormant seeds, as many as 76% of dry tropical forest species produce dormant seeds. Physical dormancy is most prevalent in dry tropical tree species and accounted for 67% of species producing dormant seeds, while only 23% showed possible physiological dormancy [43, 45]. However, experience suggests that in most of the species of tropical dry forests, the dormancy is over by the time of next rains. We may, thus, collect the seeds as and when they ripen during the year, store in cool and dry place and use for direct seeding at the onset of monsoon rains, that ensure moisture availability for extended duration.

2.3. Seed viability: Seeds of a majority of dry tropical species mature in summer and are dispersed at the beginning of the rainy season when sufficient moisture is available for germination and seedling growth [46, 47]. Experience suggests that oil-bearing seeds have low viability period and must be sown soon after collected. There is no species in tropical dry forests whose seed do not remain viable until the ensuing rainy season after ripening. We may, therefore collect these seeds as and when they ripen, store in cool and dry place and use for direct seeding during rains.

2.4. Seed size, dispersal, and soil seed bank: Dry forests are notable for a large majority of tree species with small, dry, wind-dispersed seeds, which are better able to colonize available niches than animal-dispersed plants. Small seeds and seeds with low water content have less susceptibility to desiccation in moisture-limited tropical dry regions. A vast majority of species produce seeds in the early rainy season which facilitates germination and maximizes the time to grow [44]. Small seeds have a comparatively better potential to enter into the soil and facilitate a persistent soil seed bank, necessary for autogenic and spontaneous regeneration during monsoon rains (Figure 1). The characteristics that extend seed longevity and persistence of soil seed bank are small seed size, seed dormancy, and dry condition in the field [43, 44]. Tropical dry forests also have many large-seeded, late successional, canopy trees. These species require a diversity of vertebrates seed dispersers. Many protected areas in tropical dry forest range are facing defaunation due to local extinction, natural regeneration is in these areas is seriously jeopardized. It has implication for direct seeding. We shall have more to say on this in section 3.2.

2.5. Germination niches: Identification of germination niche is necessary for seed sowing at right spots. Ideally, the microsites that are expected to have better soil seed bank in naturally intact forests are also the most appropriate germination niches. Direct seeding, thus, is either done in natural or artificially created niches and microsites. Microsites can be many: moist soils underneath natural shrubs, soil heap on the embankment of contour trenches, the trench pit (to obtain better survival in scanty rains), trenches along the fencing of the restoration area, freshly scratched and notched-up soil patches, soil bed near natural rock outcrops, scars of borrowed boulders for fencing, soil or debris heap of the contour dykes and gradonies [48]. The soil moisture regime is better in these microsites, ensuring adequate availability of moisture for germinating seeds and early establishment of sapling.

2.6. Seed sowing and germination: In areas where soil seed-bank is poor or absent, as is often the case in degraded tropical dry forests [43, 49, 50], collecting local seeds at the end of the dry season, or as and when they ripen, and seeding during the onset of rains, in appropriate natural or artificially created germination niches, increases seedling establishment, reduce the loss due seed predators, and helps in restoration of green cover. Soil moisture availability is a key factor determining the growth and survival of vegetation in tropical dry forests [51, 52]. Compared to bare ground, seeds attain higher germination--but not the establishment of seedlings-- under grass canopy which provides safety from seed predators and facilitates germination by providing a suitable microclimate with soil humidity similar to the forest. Invasive non-native species on the other hand, by altering soil moisture regime, limit native seedlings and thus do not offer similar advantage. Indeed, invasive non-native species can act as a barrier for restoration of tropical dry forests [53]. Contrary to popular opinion, soil-buried seeds do not necessarily attain higher germination. But predation and removal of unburied seeds can be large and a major causes of non-germination [11]. Not all seeds germinate synchronously. Indeed, in tropical dry forest species, germination is staggered following rainfall pulses as a strategy to stagger seedling recruitment, which ensures against unfavorable conditions [54].

While there are some rare exceptions, in general larger and healthier the seeds, better is the germination and early development. Indeed, a positive correlation between seed size and survival is found across various types of tropical forests. Also, large-seeded non-pioneer species seem to be more suitable for direct sowing than small-seeded species[55, 56]. For instance, the 34 species recommended for direct seeding in Amazonia had predominantly large seeds [57]. However, large seeds do not necessarily guarantee success if the target species becomes the favoured species of seed-predators.

Interestingly, germination and early establishment in the field are favored in shaded sites, which have milder environment and moister soil than open sites during low rainfall periods. Yet, growth of established seedlings is favored in open areas. Therefore, pruning of branches of shrubs and plants around established seedlings helps improve growth and survival of desired species in tropical dry forests. Seeds often attain better germination under a shrub or grass canopy or a protected microsite than on bare ground. Cover and microsites provide safety from seed predators and facilitate germination by providing appropriate microclimate with soil moisture similar to the forested tracts. Seeds buried in soil do not necessarily attain higher germination. However, if burying becomes necessary to avoid intense predation, the thickness of the soil layer above seeds should not exceed the thickness of the seed. Often reseeding is required as mortality in seeds and seedlings is very high due to variable precipitation and frequent dry spells.

2.7. Early root development: In general, trees that develop from direct sowing establish deeper root systems than trees raised through nursery-grown saplings. Many dry forest species form deep taproot soon after the germination and before the onset of significant growth of stem. It provides them a comparative advantage when sown directly [20, 58].

3. Implementing direct seeding

Several valuable species of shrubs and tree species can be established in the field directly from seed. Direct seeding involves collecting seeds from local sources, storing them until sowing, identifying the germination niches or preparation of seed-beds to optimize the germination, and sowing seeds at the onset of monsoon season. In general, world-wide experience suggests that direct seeding is a useful method for restoration of tropical dry forests (Table 1).

3.1. Species for creating multifunctional ecosystems: The science on achieving restoration in which resulting vegetation is multifunctional tropical dry forests is not very well developed. However, some guidance from experiential knowledge is available [4, 18, 48, 58-63]. It is very useful to identify the context-specific species for direct sowing guided by seven criteria that are in coherence with ecological, economic and social sustainability:

1. Multiple use local species that yield forest products to support livelihoods of the communities.
2. Reasonably fast growth with dense spreading canopies which rapidly shade out weeds, act as nurse plants, or have facilitation effect in subsequent autogenic regeneration.
3. Ease of collection and storage of seeds, but without compromising the intended diversity and mixture of species.
4. A reasonable success in direct seeding, but without compromising desired aim of diversity.
5. Edible and useful species for wildlife (such as fruit and nectar or perching and nesting sites), because birds attracted by such species disperse seeds of other species into the restoration sites.
6. Preponderance of leguminous species, because they enhance soil microbial biomass and N mineralization and promote growth of other saplings growing in their vicinity.
7. Cultural and ecological keystone species and sacred species as they are ecologically important and socio-culturally valued. Direct sowing of such species may enhance natural seed dispersal and accelerate succession.

One innovative approach to restoration of tropical dry forests is the 'framework species method' which involves planting or direct sowing of 30 to 40 indigenous forest tree species from different families to re-establish a basic forest structure that catalyses the recovery of biodiversity [64-67]. While selecting the species for direct seeding we should clearly need to keep in mind the ecological, economic and social desirability. Multiple use trees, shrubs, and herbs suitable for direct seeding should form the pool of species for direct sowing. Using large number of species from both early and later successional stages as well as leguminous and non-leguminous species, results into higher initial diversity that may also be supplemented by colonization from nearby forest remnants, if present. This is also beneficial in terms of ecological services, and at a later stage, supply of economically valued products to society [48, 68-70].

3.2. Suitable species for direct sowing: Species often successfully established by direct sowing are generally those that have large (>0.1 g dry mass), spherical seeds with medium moisture content (36–70%), and large food reserves, so they can survive longer than smaller seeds and produce more robust seedlings [4, 34]. Large, round or spherical seeds with tough and smooth seed coat are less prone to predation. For instance, legume seeds typically have tough, smooth seed coats, making them resistant to desiccation and predation. Also, the nitrogen-fixing capability of many legume species gives them a competitive advantage over weeds [4]. Early-successional and pioneer species, with their ability to grow rapidly, are often suggested to be more appropriate for direct sowing. Yet, late-successional and climax tree species can also be successfully established by direct seeding. Indeed, by virtue of their large seeds and food reserves, the seeds of climax forest trees provide much better result in tropical dry forests [4, 48, 71]. Large-seeded species often require vertebrate-seed dispersers [72-75]. For instance, in tropical dry forests of Madagascar, out of the 52 species, the brown lemur (*Eulemur fulvus fulvus*) dispersed 29 and 13 species with small and large seeds. With the local extinction of large, vertebrate seed-dispersers over much of their former ranges of occurrence, direct seeding may be the only way that the large seeds of climax tree species can reach restoration sites [4].

3.3. Direct sowing experience in Rajasthan, India: As direct sowing is a simple, easily followed and people-friendly restoration technique, people living in and around tropical dry forests have developed various ethnoforestry practices based on direct sowing [58, 76]. People in southern Aravallis have been using direct sowing methods to regenerate livelihood trees such as *Madhuca indica*, *Syzygium cuminii*, *Butea monosperma*, *Phoenix sylvestris*, *Zizyphus* sps., *Mangifera indica*, *Azadirachta indica* and several other species across landscape (Figure 1 to 4).

Direct sowing requires simple technique for rainwater harvesting in combination with soil manipulation to prepare seeding beds before sowing (Figure 4). Depending upon the locality factors such as soil, aspect, moisture, ground slope and availability of natural rootstock, location specific plans are drawn. Direct sowing with different combinations has been practiced in Vindhyas and Aravallis in Rajasthan. The most successful combinations are (i) seeding and sprouting enhancement, (ii) seeding, sprouting, and minimal planting, (iii) seeding and natural regeneration, and sowing under *Euphorbia* and other shrubs. Out of all these, the least costly and most useful model is direct sowing combined with assistance to the natural regeneration through sprouting of persistent rootstock.

Direct sowing and sprouting enhancement: After fencing the restoration area to exclude cattle, direct sowing is undertaken in combination with rainwater harvesting structures such as contour trenches and v-ditches. Combining rainwater harvesting also promotes sprouting of the persistent rootstock of several species. Trench mounds and saucer shaped micro-catchments around a planted sapling are used as bed for direct sowing.

Direct sowing, sprouting and minimal plantation: This has now become the standard restoration technique in degraded tropical dry forests in several parts of India. Depending upon the terrain, soil, moisture and availability of rootstock, a combination of direct sowing, planting of nursery-raised saplings and assistance to natural regeneration is implemented.

Direct sowing and natural regeneration: This technique has several advantages. Being a low cost venture it is prominently included in participatory strategy. Areas containing persistent rootstock and scattered remnant trees are ideal for direct sowing in combination with facilitated natural regeneration through coppice and soil seed bank. Initially, restoration area is fenced in advance to provide protection for sprouting and seed germination from soil seed bank. The soil and water conservation structures such as staggered contour trenches, continuous trenches, v-ditches, contour dykes, check dams and percolation ponds are dug. This ensures adequate availability of moisture for germinating seeds and seedlings. Seeds of people's choice are sown under *Euphorbia* bushes, dug-up soil of trenches, trench pits, along the fencing, notched-up and scrapped soil patches, trapped soil in rocky outcrops, scars of borrowed boulders for fencing, backside of contour dykes and gradonies. All these structures act as germination niches.

Apart from direct sowing, assistance to natural regeneration is provided by cutback to degraded stock, cultural operation in bamboo clumps, making water-harvesting saucer-shaped micro-catchments around germinating seedlings from persistent soil seed bank, stem singling in multiple coppice and circular trenching for inducement of root suckers around the trees of suitable species such as *Boswellia serrata* and *Diospyros melanoxylon*. This combination enhances productivity and biodiversity in restoration area.

Depending upon the stated preference of the local people, species for timber, fodder, fuel, fruit, oil, medicines and other non-timber forest products are chosen for direct sowing. In the past, only spiny and xerophytic species were tried. However, now about 50 species are directly sown. Some of the multiple-use species that are giving good success include *Madhuca indica*, *Syzygium cuminii*, *Butea monosperma*, *Phoenix sylvestris*, *Zizyphus* sps., *Mangifera indica*, *Azadirachta indica*, *Pongamia pinnata*, *Tamarindus indica*, *Terminalia arjuna*, *Terminalia bellerica, Acacia catechu*, *Acacia nilotica*, *Acacia leucophloea*, *Acacia senegal*, *Aegle marmelos*, *Emblica officinalis*, *Holoptelia integrifolia*, *Annona squamosa*, and *Boswellia serrata* among others. Sample count in 2 to 10 years old plantations over 20,000 ha area in Aravallis suggests about 50% survival of directly sown and germinated seedlings in the long-term.

3.4. Enrichment sowing under shrubs and bushes: Rajasthan has traditions of maintaining the shrubs in pastures and sacred areas locally called as *Orans*. Apparently, these shrubs seem to interfere with the growth of grass for grazing. However, the fact is that these shrubs have vital role in enhancing the soil-moisture regimes in arid environments and thus can help in restoration of dry lands [63, 76]. The relatively high soil moisture at the upslope direction of each shrub enhances annuals growth producing a positive feedback loop: soil moisture –annuals growth maintaining the typical spatial organization and contributes to the sustainability of the grazing system [77].

Euphorbia or Thor, as it is popularly known, is found over many localities in Rajasthan. In southern dry mixed deciduous forests of Mount Abu and Udaipur, it may grow upto an elevation of 1500 m with *Anogeissus* and *Phoenix sylvestris* associations. It is a shrub that thrives even on the barest grounds of Aravallis throughout Rajasthan. In northern dry mixed deciduous forests it is found around the forest patches occasionally mixing mainly with species such as *Anogeissus latifolia*, *Boswellia serrata*, *Lannea coromandelica*, *Sterculia urens*, *Bombax ceiba*, *Soymida febrifuga*, *Albizzia odoratissima*, *Acacia leucophloea*, *Emblica officinalis*, *Wrightia tomentosa*, *Wrightia tinctoria*, *Haldina cordifolia* and *Mitragyna parvifolia*. Thor is also found in various degradation stages of dry deciduous forests. There are at least four species of *Euphorbia* that develop into bush or shrubs; these are Thor *Euphorbia caducifolia*, Danda Thor *Euphorbia nerifolia*, Ghota Thor *Euphorbia nivulia* and another species *Euphorbia royleana*.

Thor bushes also support many species of herbs, shrubs, climbers and trees. On barren hill slope and rocky outcrops, where Euphoria has a remarkable ability to grow, many species of plants can only be found thriving in the shelter of large bushes. Experience in Udaipur, Dungarpur, Chittorgarh, Banswara and Sirohi districts of Rajasthan suggests that natural regeneration of following species is frequently found in the shelter of Euphorbia bushes [48, 58, 76]:

- **Shrubs and Climbers:** *Calotropis procera, Adhatoda zeylonica, Cuscuta reflexa, Cassia auriculata, Withania somnifera, Acacia jacquemonti, Woodfordia fruticosa, Abrus precatorius, Plumbago zeylonica, Tephrosia purpurea, Holarrhena antidysenterica, Grewia villosa, Tinospora cordifolia, Vitex negundo, Asperagus racemosus, Zizyphus nummularia,* and *Jatropha curcus.*

• **Trees:** *Emblica officinalis, Cassia fistula, Dichrostachys cinerea, Ailanthus excelsa, Melia azadarach, Ficus benghalensis, Aegle marmelos Zizypuhus mauritiana, Santalum album, Holoptelia integrifolia, Anogeissus latifolia, Anogeissus pendula, Wrightia tinctoria, Butea monosperma, Lannea coromandelica, Cordia dichotoma, Balanites aegyptica, Flacourtia indica, Capparis decidua, Acacia catechu, Acacia senegal, Madhuca longifolia, Azadirachta indica, Acacia leucophloea, Boswellia serrata, Bombax ceiba,* and *Annona squamosa*.

Natural regeneration of plants under Euphorbia bushes depends upon availability of remnant trees as a seed source, seed production, seed dispersal, seed germination and sapling establishment. When fertile seeds of a species are produced in adequate quantities, there is a likelihood of some seeds reaching Euphorbia bushes through various modes of dispersal, such as wind, water, gravity, birds and animals. Facilitation effect of Euphorbia bushes is mainly the result of several factors (Figure 3):

1. Adequate soil and humus under Thor bushes.

2. Moisture regime under Thor bush is favourable for germination and establishment. Mulching effect of shade reduces the loss and increases the availability of moisture to saplings during the periods of scarcity.

3. Protection of germinating seed against trampling by cattle.

4. Protection of saplings from grazing and browsing as they grow amidst protection of thorny branches of Thor.

5. Lateral competition with Thor branches for light induces the apical growth and formation of a clean and straight stem in the tree saplings.

6. Since trees have comparatively deeper root system there is no competition for nutrients with Thor roots.

This facilitation ability has been used in restoration efforts. To help the regeneration and establishment of shrubs and trees on the refractory sites, direct seeding of many species, under Thor bushes, has been tried with satisfactory results. A major part of Aravalli landscape is dotted with Thor bushes; dibbling of seeds of desired species under these bushes enhances the biodiversity of otherwise barren landscapes. Before the onset of monsoon a small patch (10 cm x 10 cm x 10 cm) of soil under Thor bushes is scrapped with the help of iron or wooden tool to loosen the soil and 3 to 4 seeds of desired species are sown. Since Thor bushes are more or less evenly spaced and distributed over large tracts, sowing automatically gets spaced and saplings can easily be traced for subsequent silvicultural operation. The technique is a low cost venture hence suits participatory strategies of forest regeneration.

In general, seedlings originated from direct sowing benefit from saucer-shaped microcatchment around them for moisture conservation, weeding and hoeing, early thinning and spacing in the first year. Resowing in case of failure in various patches, including sowing of new species of herbs, shrubs and trees may also be required. If seedlings have suffered from die back during the first year then 10 to 15 new shoots resprout in subsequent rains. It will require shoot singling. Usually, however, no post-sowing silvicultural operation is required for the saplings sown in thor bushes.

4. Overcoming the challenges of seeds and seedling in direct sowing

Despite the benefits of direct sowing, the initial phase of seedling establishment seems to be the most critical. The lower survivorship among directly sown seeds may be overcome by sowing more seeds or selecting for more vigorous seeds, although this will obviously increase the costs of seed collection, storage, and competition between future seedlings within seed spots [55]. After direct sowing, any mortality among the newly emerged seedlings will result in non-uniform stands, and may require re-seeding.

In the field, a very low percentage of dispersed tree seeds germinate and even fewer seedlings survive to finally attain the size of mature trees. The same is true of direct seed sowing. Some of the challenges associated with sown seeds and seedlings include: i) desiccation, ii) seed predation by ants and rodents and iii) competition from herbaceous weeds. By addressing these factors, it is possible to improve the rates of germination and seedling survival above those for naturally dispersed seeds [4].

Though direct sowing offers several advantages, it also requires high quantity of seeds to be sown. Sometimes a brief shower followed by a long dry-spell may kill all the germinated seedlings. Such episodes necessitate re-sowing, with additional cost. Since seedlings take longer time to reach beyond browsing height, it becomes essential to provide protection to the restoration site to exclude cattle for a longer duration. Direct sowing also demands care to judge the genetic soundness of seed-stock being sown, whereas choosing a sapling by morphological examination is far easier.

Promotion of propagule supply through direct seeding without first preparing the soil and ground conditions may not provide much success. In general, there is an appreciable trend for interventions that combined manipulation of ground conditions with actions to increase propagule supply to be the most consistent in promoting positive progress toward restoring forest structure. This general pattern remains evident even after accounting for the potential confounding influence of the duration of intervention [78].

The problem of desiccation can be overcome by selecting tree species whose seeds are tolerant of or resistant to desiccation (i.e. those with thick seed coats) and by burying the seeds or laying mulch over the seeding points [79]. Burying can also reduce seed predation by making the seeds more difficult to find. Pre-sowing seed treatments that accelerate germination can reduce the time available for seed predators to find the seeds. Once germination commences, the nutritional value of seeds and their attractiveness to predators decline rapidly. But treatments that break the seed coat and expose the cotyledons sometimes increase the risk of desiccation or make seeds more attractive to ants [4, 79]. Conservation of raptors and carnivores can help to control rodent populations and reduce seed predation [4].
Seedlings that germinate from seeds are initially small compared to planted, nursery-raised saplings. Weeding around the seedlings is necessary and it must be carefully carried out. While weeding can increase the cost of direct seeding, it can contribute greatly to success [13, 80, 81].

While there are many studies that have on direct seeding, none has identified the critical characteristics that a specific species requires for successful establishment when directly sown in tropical dry forests. The technique may prove costly for some of the species that do not come up well through direct sowing. For example, Establishment costs for six Asian dioecious *Ficus* species such as *Ficus auriculata, F. fulva, F. hispida, F. oligodon, F. semicordata, and F. variegata* calculated on the basis of "per plant established" were $1.14 for seed, $6.95 for cutting, and $25.88

for direct seeding [82]. Seedling mortality could be large in very dry regions. In an experiment in Rajasthan although germination percent of Azadirachta indica was 53.9 (population of 27500 seedlings ha^{-1}, survival by subsequent year dropped to as low as 1.2% [83] .

Soil seed bank is helpful in facilitating regeneration, but the challenge in tropical dry forests is that seed bank is often poor, and may contain large percentage of invasive species. It can thus act as a source of invasion. Also, germination and recruitment of tree seedlings of indigenous species may confront a formidable competition from invasive and exotic herbs and shrubs present in the seed bank. For example, species diversity and density of buried seed bank in top 10 cm. of soil in tropical dry deciduous forests in Central India found that seeds of total 34 species were present in soil (17 species of trees, 4 of shrubs and 13 of herbs). The highest density in upper layer (0-5 cm) was of *Anogeissus pendula* (800 seeds m^2) under inter canopy area. Maximum densities in case of shrub and herb species was contributed by invasive *Lantana camara* (175 seeds m^2) under canopy and *Cassia tora* (850 seeds m^2) under inter canopy [84].

While remnant vegetation is a good source of soil seed bank, it is no guarantee for representation of all the species that exist in the region. There is often poor species richness and composition in soil seed banks compared to above ground vegetation in degraded tropical dry forests [49, 85]. Restoration of such areas require careful selection of species for direct sowing. In case the seed availability becomes a challenge, it would be useful to collect the top soil from beneath tree canopies, that have good seed availability in the soil at the end of the dry season. Collecting this transient seed bank (i.e., litter and soil) from intact tropical dry forests at the end of the dry season and disposing it onto restoration area may be a promising strategy for dry forest restoration [44]. Such seed banks may also have seeds of weeds, and thus a careful weeding may be necessary subsequently.

5. Conclusion

Our comprehensive review provides a synthesis of science and practitioner's perspective on the usefulness of direct seeding as a method for the tropical dry forest restoration. Our exploration of the major factors that have relevance for direct seeding in tropical dry forests, implementation aspects of direct seeding, and the synthesis of science and our experience is instructive for both scientists and practitioners. Despite the practical advantages of direct seeding, the technique remains underutilized due to both a lack of awareness among practitioners as well as robust research demonstrating its effectiveness in tropical dry forests. As the review brings out, enough is known to permit large-scale implementation of direct seeding for restoration of tropical dry forests. On the other hand, several issues that remain to be understood through robust research can be rewarding to scientists.

Table 1: Examples of tropical dry forest restoration through direct seeding

No.	Geographical Location	Species	Restoration interventions	Reference
1	India	Large number of species in various locations of tropical dry region and dry deciduous forests including *Acacia nilotica, Acacia catechu,Ailanthus excelsa, Azadirachta indica, Dalbergia sissoo, Derris indica, Emblica officinalis, Tamarindus indica, Terminalia bellirica, Pterocarpus marsupium, Bombax ceiba, Ougeinia oojeinensis, Madhuca longifolia* var. *latifolia, Hardwickia binata, Dalbergia latifolia, Albizzia amara, Albizzia lebbeck, Santalum album, Holoptelia integrifolia,Bauhinia racemosa, Bauhinia variegata, Butea monosperma, Cassia fistula, Chloroxylon swietenia, Diospyron melanoxylon, Hymenodictyon excelsum, Sterculia urens, Terminalia arjuna, Zizyphus sps.*	Soil and moisture conservation structures, direct sowing in freshly exposed soil at the onset of monsoon rains	Ghosh, 1977 [71] See also,[86-96] for earlier efforts of in India.
2.	Udaipur, India	Large-scale implementation as described in the main text	As described in the main text	Pandey, 1991, 1996, 1998 [48, 58, 62]
3.	Singrauli, Madhya Pradesh, India	The leguminous forbs *Stylosanthes hamata* and the grasses *Pennisetum pedicellatum* and *Heteropogon contortus* were sown along with *Leucaena leucocephala*, *Terminalia arjuna*, *Syzygium cumini, Azadirachta indica, Terminalia bellirica*, *Acacia catechu*, *Acacia nilotica*, *Madhuca indica*, *Pongamia pinnata*, and *Ziziphus jujuba* syn. *Z. mauritiana*	Mixture of tree species and grasses and forbs rapidly stabilizes coal mine spoil, and can accelerate natural plant succession, as the ground cover acts as a nurse crop and can trap air-borne seeds.	Jha *et al.*, 2000 [97]
4.	Singrauli, Madhya Pradesh, India	(a) 24 species of legumes, non-legumes, forbs and crops (b) *Acacia catechu, Acacia nilotica, Azadirachta indica, Madhuca longifolia, Pongamia pinnata, Syzygium cumini, Terminalia arjuna, Zizyphus jujuba*	All species performed well and were able to establish in both the experiments in coal mine spoil.	Jha and Singh, 1993 [98], Singh and Singh, 2006 [19]
5.	São Paulo State, Brazil	*Enterolobium contorstisliquum*, *Chorisia speciosa*, *Schizolobium paraphyba*, *Mimosa scrabella*	Herbicide application, weeding around germinated seedlings, protection to several species that came up naturally in seeding area	Engel and Parrotta, 2001 [16]

6.	São Paulo State University at Botucatu, Brazil	*Enterolobium contorstisliquum*, *Schizolobium paraphyba,*	Sowing lines prepared to 40 cm depth with a soil ripper, Legume dominated but species poor mixture of early-successional species gave better overall results than and a species-diverse, legume-poor mixture.	Siddique *et al.*, 2008 [31]
7.	São Paulo State, Brazil	*Acacia polyphylla, Enterolobium contortisiliquum, Mimosa bimucronata, Parapiptadenia rigida, Erythrina speciosa, Poecilanthe parviflora*	Rhizobia inoculation in indigenous leguminous species and sowing of 20 seeds per meter row in a riparian zone. Rhizobia inoculation did not affect seedling emergence and early growth.	Soares and Rodrigues, 2008 [99]
8.	Brazil	Direct sowing: *Achatocarpus pubescens, Annona cacans, Cordia ecalyculata, Diospyros brasiliensis, Euterpe edulis, Geophila repens, Myrocarpus frondosus, Piper aduncum, Vitex montevidensis*	Transfer of soil and litter from mature forests and direct sowing. From litter, 14 species germinated and in the direct sowing experiment, *Achatocarpus pubescens* and *Cordia ecalyculata* gave good results, and *Diospyros brasiliensis* gave the best germination (near 50%)	Suganuma *et al.*, 2008 [100]
9.	Santana San Francisco County, Brazil	*Enterolobium contortisiliquum*, *Hymenaea courbaril, Cassia grandis, Schinus terebinthifolius, Caesalpinia leiostachya*	Restoration of riparian forests by direct sowing is achievable.	Ferreira *et al.,* 2009 [101]
10.	Dry forest pastures, Brazil,	*Amburana cearensis, Aspidosperma parvifolium, Cedrela fissilis, Enterolobium contortisiliquum, Eugenia dysenterica, Guazuma ulmifolia, Machaerium scleroxylon*	Seed sowing (buried and unburied) gave higher germination under a grass canopy than on bare ground. Buried seeds did not show higher germination.	Guarino and Scariot, 2014 [11]
11.	The Kaupulehu Preserve, Hawai	Tree: *Kokia drynarioides,* Shrub: *Colubrina oppositifolia, Sophora chrysophylla, Sida fallax,* Herb/Vine: *Cyperus hillebrandii*	Grass control and shade helps in regeneration of native species	Cabin *et al.*, 2002 [12]
12.	Yucatan peninsula, Mexico	*Brosimum alicastrum, Enterolobium cyclocarpum, Manilkara zapota*	Direct seeding of shade-tolerant, later-successional species (useful diet of spider monkey), in mature and young forests, 5–41% of seeds germinated, and 3–35% reached the seedling stage. Direct seeding is more useful when secondary growth cover has developed.	Bonilla-Moheno and Holl, 2010 [15]
13.	Quintana Roo, Mexico	*Swietenia macrophylla*	Creating different levels of overstorey removal, dibbling / dropping and burying seeds 0.5 cm in soil.	Negreros-Castillo and Hall, 1996 [102]
14.	Central Veracruz, Mexico	*Brosimum alicastrum, Enterolobium cyclocarpum*	Direct sowing of large-seeded zoochorous canopy tree species. *Enterolobium* seedling survival and growth higher in open habitats (60% survival) than in habitats shaded by woody plants (<10%). *Brosimum*, the reverse was true as it survived and grew better under a dense woody canopy (>80% survival) than in open sites (0%).	Laborde and Ferrayola, 2012 [56]

15.	Hellshire Hills protected area, Jamaica	*Calyptranthes pallens*, *Eugenia* sp., *Hypelate trifolia*, *Metopium brownii*	Seed sowing in shade with supplemental watering gave better results.	McLaren and McDonald, 2003 [103]

Figure 1: Spontaneous or autogenic regeneration of Neem (*Azadirachta indica*), beneath an old *Acacia* tree, through bird-dispersed seeds, after protection was initiated in 2005 in Rajasthan. There are about 50 such patches in this 108 acres of urban forest restoration area. Mimicking this natural process (i.e., seed addition through direct seeding) in seed-limited soils has been very successful. In order to encourage the autogenic regeneration, soil should remain undisturbed from trampling, sweeping, and debris cleaning. This helps in humus build-up and carbon accumulation in soils. Seeds deposited in such humus-rich soils germinate and grow.

Figure 2: Tropical dry forests have remarkable resilience that allows these threatened ecosystems to come back quickly, both through dormant root-stock as well as natural seed dispersal, direct sowing, germination and establishment process.

Figure 3: *Azadirachta indica* saplings growing amidst Euphorbia shrubs, Jaipur, Rajasthan, India. In water-limited tropical dry forests, in early stages of life some plants benefit from growing in close proximity to others that mitigate extreme conditions, improve nutrient availability, and protect against grazing, trampling and herbivory. This facilitation by nurse-plants has implications for forest restoration through direct seeding and the establishment of desired species, mimicking the natural phenomenon.

Figure 4: Results of the direct sowing of bio-fuel species, *Jatropha curcus* and *Acacia senegal*, Rajasthan, India. Rainwater harvesting structures provide a microhabitat for germination and growth by enhancing the availability of moisture in early stages. Saplings in these germination niches have better chances of establishment of plants in tropical dry forests. Rainwater harvesting and direct seeding effectively enhances vegetation cover and productivity of the degraded dry tropics.

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