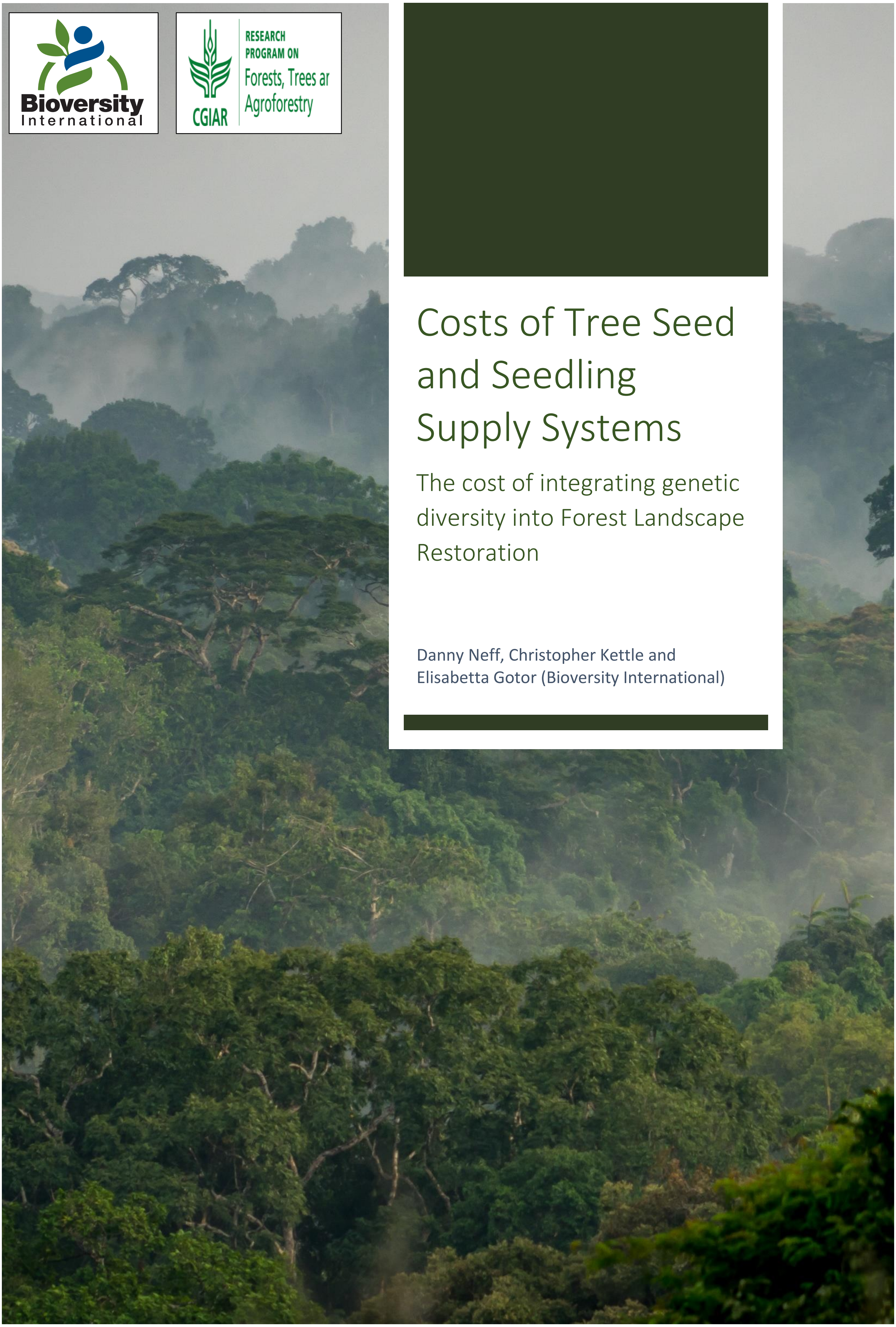

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Costs of Tree Seed and Seedling Supply Systems

The cost of integrating genetic diversity into Forest Landscape Restoration

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Abstract

Genetic and physiological quality are crucial for the short and long-term success of restoration projects. While physiological quality has a considerable influence on both the germination rate of seedlings and the immediate vitality of the seedling after planting, genetic quality enables a planted population to adapt to a changing environment, and positively correlates with an increased resilience to pests and diseases. Moreover, genetic quality is considered to be an important prerequisite that allows seedlings to establish under prevailing conditions at the planting site and thus to avoid or decrease mortality due to maladaptation. Although there is broad consensus about the advantages of integrating genetic quality into Forest Landscape Restoration (FLR), markets often fail to offer seed of high genetic quality, resulting in genetic quality hardly being considered in current restoration projects. Besides the possible lack of appropriate guidelines or a general lack of awareness about the importance of genetic diversity, a collection strategy that prefers quantity over (genetic) quality might also be a reason for this. It may be economically feasible to collect as many seeds as possible from a few nearby trees, but the disadvantages of this strategy far outweigh the advantages. The resulting lack of genetic quality potentially leads to a (total) failure of a restoration initiatives, which ultimately entails a loss of investment and hence comes with significantly higher costs compared to the costs that were saved during collection.

In order to better understand the interrelationships between costs, benefits, properties of the supply chain (e.g., vegetation cover at the planting site), and quality considerations (physical, physiological, plant health, and genetic) we developed a cost model that integrates relevant cost drivers of the tree seed and seedling supply chain into a single cost structure. By presenting a holistic view of relevant cause-effect relationships, we aim to help decision makers and practitioners to take better informed decisions and to create appropriate incentives, which are reflected, for example, in genetic quality-dependent prices for seeds. The model is based on a framework that represents important components of and interrelations within currently applied seed sourcing strategies, as well as associated costs and mechanisms to which these costs are subjected.

The framework is based on literature and expert interviews. During the development of the framework it became apparent that estimates on restoration costs are subject to considerable variation. Furthermore, in most cases where costs were presented explicitly, their composition remained unknown. These uncertainties have been transferred to the model accordingly. It is therefore important to validate the model in a next step and populate it with data from the field, instead of secondary data.

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1. Introduction

Doubtless, the loss of forests and the associated impacts on the environment and the society are among the greatest environmental threats of our time (Millennium Ecosystem Assessment, 2005). Governmental and Non-governmental organisations have instituted programmes that aim to slow or stop deforestation and, where possible, to reverse it. Political commitments at national and international level have been made, which now need to be translated into adequate policies, as well as concrete budget allocations. According to the Bonn Challenge, the potential for reforestation is enormous and thus the goals are ambitious. Up to 350 million hectares of degraded land will be restored by 2030. Accordingly, the required financial resources are also high. How much these efforts will cost in the end, however, is difficult to quantify. Various studies provide estimates of restoration costs for different scenarios. The presented costs vary significantly between and also within different regions. For example, while Cole et al. (2011) recorded establishment costs for planting nursery-raised seedlings in Brazil that, depending on site conditions, range from US$ 1750 ha^{-1} to US$ 2735 ha^{-1}, Rodriguez et al. (2011) calculated for the same planting method and the same region establishment costs of US$ 5175 ha^{-1}. In their study, Summers, Bryan, Nolan, & Hobbs (2015) have found establishment cost estimates ranging from around US$180 ha^{-1} to more than US$36000 ha^{-1}. Although there is consensus that the costs of restoration are justified because they are relatively moderate compared to the costs incurred if no measures are taken (Chazdon et al., 2017), this considerable variation shows that some doubts about the economic viability of at least some restoration projects are justified (Summers et al., 2015).

Therefore, an efficient use of resources is indispensable. Efficient in this context is not defined by planting as many trees as possible per capital invested, but by the long-term establishment of a tree population that serves the aim of the restoration. This in turn depends in particular on the ability of the planted trees to establish in a given environment and thus to survive under the current conditions of a planting site. Moreover, and especially against the background of anticipated climate change, the planted tree population should be capable of adapting to changing environmental conditions. For this reason, the genetic quality of the planted stock plays a decisive role. A high genetic diversity, as part of genetic quality, is reflected not only in an increased vitality but also provides the necessary basis for trees to build resistance to pests and diseases, and to adapt to changing conditions (Alfaro et al., 2014; Charlesworth & Willis, 2009; Graudal et al., 2014; Jalonen, Valette, Boshier, Duminil, & Thomas, 2018; Kettle, Ennos, Jaffre, Gardner, & Hollingsworth, 2008). Furthermore, genetic quality and in particular genetic diversity is an important prerequisite for ecosystems to be able to provide services that support and strengthen the functionality of ecosystems and with that contribute to a high biodiversity as well as to secure the livelihoods of local communities (Dawson et al., 2014; Wymore et al., 2014). In view of these facts, it is surprising that the potential of genetic diversity has often not been used or neglected in restoration projects (Alfaro et al., 2014; Bozzano et al., 2014; Dawson et al., 2014; Dedefo, Derero, Tesfaye, & Muriuki, 2017; Graudal & Lillesø, 2007; Neto et al., 2014; Roshetko et al., 2018; Thomas et al., 2014). For example, it is not uncommon in projects that the collected seeds originate from only a few mother trees (Dedefo et al., 2017), which, for example, results in a narrow genetic basis, which, in turn, is a poor prerequisite for the vitality and resilience of a plant population. (Kettle et al., 2008). In addition, Roshetko et al. (2018) have shown in their study that only about a third of the project plans examined contained indications that project designers had, to some extent, included site matching or local adaptation of planting material in their planning. Although it cannot be ruled out that some actors simply do not know how to achieve a sufficiently high genetic quality, in principal, the necessary aspects and techniques are well known (Graudal & Lillesø, 2007). The question therefore arises as to why genetic quality does not receive more attention in projects. Jalonen et al. (2014) suggest, *inter alia*, that a lack of awareness about the importance of genetic diversity or a lack of appropriate guidelines may contribute to this. Dedefo (2017) sees the cause in economic considerations where the emphasis is on mass seedling production and therefore quantity is more important than quality. Schmidt (2000; 2007) also argues that economic incentives result in collecting as many seeds as possible with the least possible investment, using methods which often do not result in achieving the best quality. From an overall economic point of view, however, costs are being saved in the wrong place with this strategy. Both poor genetic and physical quality of the plant material can quickly lead to failures that ultimately cause more costs than they were supposed to save.

In order to integrate these action mechanisms into a single cost structure, we developed a framework and, based on that, a cost model. The aim of this cost model is twofold: besides offering a holistic view of the cause-effect relationships, it allows us to predict the cost of tree seed and seedling supply for four different methods of landscape restoration: direct seeding, planting nursery-raised seedlings and nursery-realised cuttings, and planting stakes. In contrast to the existing cost models (see for example Summer et al. (2015)), our cost model focuses on the effects of genetic as well as physiological quality of seeds and seedlings on costs. Quality was not considered as a cost factor in any of the models we examined.

In a first step, we introduce crucial components of the tree seed and seedling supply system. In the following, we focus on where in the system costs are incurred and how they are influenced.

2. Tree seed and seedling supply system

Properties of tree seed supply systems may vary greatly depending on the local context. There are various ways in which different actors produce, distribute and plant tree seed and seedlings. This variety not least derives from different national policy frameworks that are actively shaping involved actors' room for manoeuvre. Often these policies have resulted in national programmes with different foci. Whereas some programmes are mainly supporting the formal plantation sector others concentrate more on rural development (Graudal & Lillesø, 2007). Depending on the focus, these programmes have, for example, different effects on the economic competitiveness of different actors by creating distorted markets and unilateral incentives (Graudal & Lillesø, 2007), which, in turn, has significantly shaped tree supply systems.

The system image presented in Figure 1 illustrates the tree supply system in a simplified form and yet claims to represent the most important properties and components of, and interdependencies within, the system.

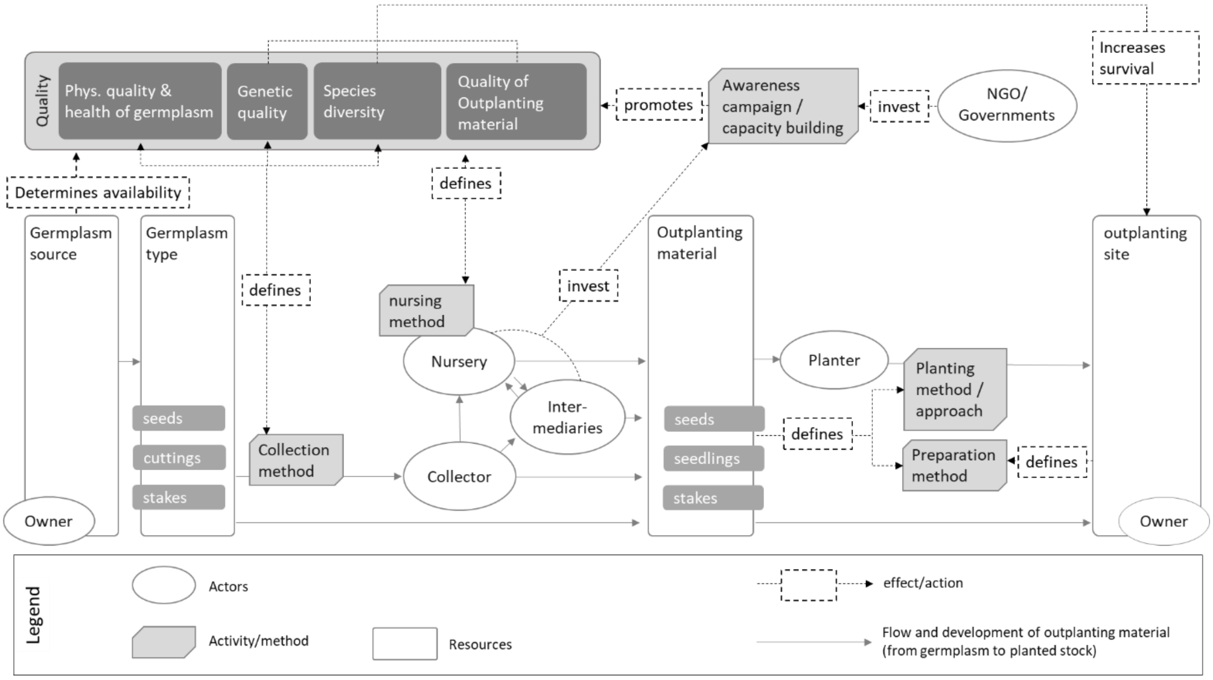

Figure 1: Tree seed and seedling supply system with key components of and interrelations within currently applied seed sourcing strategies. Furthermore, it shows which aspects/components of the system are affected if quality issues (incl. genetic diversity) are taken into consideration.

We distinguish between four different system components; **Resources** (source of germplasm and outplanting site), **variables** (germplasm and outplanting material) with relate characteristics (e.g. quality of germplasm or genetic quality), **actors** (e.g. owners, nursery, collector, etc.) and **actions** with connected methods and activities (e.g. capacity building, collection method, etc.). The linkages between components are either representing possible **flows** (of planting material) or how different system components and characteristics are **linked** with each other (dashed arrows). In the following, we provide a more detailed elaboration of each system property and interlinkages.

2.1 Resources

2.1.1 Source of germplasm and owner

There are several ways of categorizing sources of germplasm. Most authors distinguish between forests, plantations, orchards and farmland. These categories again can be divided in subcategories, that additionally reflect management practices. Forests, for example, can be undisturbed and integer or managed to several degrees. As important as current management practices are practices of the past. Because it is the history of a site that is to a large extent crucial for the genetic diversity and thus for an essential property of the quality of the germplasm (see section 3.2, 'The cost of collection'). In addition to management practices, ownership is another crucial characteristic, especially because this tend to determine which actors most typically control the source and hence who has access to it.

Forests: Most of the germplasm is collected primarily in forests that are either natural or restored or planted (plantations) (Dedefo et al., 2017; Gregorio, Herbohn, & Harrison, 2010; R. Jalonen, Valette, Boshier, Duminil, & Thomas, 2018). In some cases, stands of trees in either natural forests or plantation have been improved by appropriate management for the specific purpose of seed production. These improved stands are called Seed production areas (SPAs) (Mulawarman, Roshetko, Sasongko, & Iriantono, 2003) Whereas in the global study of Jalonen et al. (2018) mainly natural forests were mentioned as being the major source of germplasm, the opposite was the case for the study of Dedefo (2017) in Ethiopia, where plantations were the most important sources for tree seeds. Besides the constraints resulting from fragmentation, natural forest may also have degraded genetic quality because the best quality trees have been harvested (Mulawarman et al., 2003). Where this has not been the case, natural forests generally contain a large range of useful tree species of high genetic quality (Graudal & Lillesø, 2007; Mortlock, 1999). However, that potential is rarely utilised (Graudal & Lillesø, 2007). Forests are mainly controlled and owned by government and, moreover, are often protected (Graudal & Lillesø, 2007). This comes with respective restrictions on collectors to carry out collection of high quality seeds (Graudal & Lillesø, 2007; Schmidt, 2000).

Farmland: 6% of the forest restoration projects that have been surveyed by Jalonen et al. (2018) stated that farmland was their main source of germplasm. This proportion coincided exactly with the results from a survey among tree nurseries in Ethiopia (Dedefo et al., 2017). Trees on farms are either remnants of natural vegetation or planted (Graudal & Lillesø, 2007). Due to isolation of the trees on farmland and their often unclear origin, the genetic quality is as dubious (Graudal & Lillesø, 2007). Mainly owned or at least controlled by smallholders, the access is accordingly granted to the smallholders themselves. It is not surprising that farmland is therefore the most important source type for germplasm for farmers (Graudal & Lillesø, 2007). Outside the farm, the seeds from farm trees are probably mainly distributed by NGOs (Graudal & Lillesø, 2007).

Seed orchards: Seed orchards normally contain only a very limited number of species and genetic variability, but in many cases the genetic variability is reasonably good for seed production (Graudal & Lillesø, 2007; Prescher, Lindgren, & Karlsson, 2008; Stoehr, Webber, & Woods, 2004). According to Jalonen et al. (2018), for 8 % of the forest restoration projects seed orchards are their main source of germplasm. In some areas, seed orchards are the major source for seeds. In British Columbia, Canada, for example, about 40 % of the seeds for reforestation programmes are sources from seed orchards (Stoehr et al., 2004). According to Graudal & Lillesø (2007), seed orchards are almost exclusively established on governmental land and only in few cases on other types of land. Accordingly, governmental bodies, or in some cases research organisations, most often controll collection and distribution of seeds from distribution is most often controlled by government.

2.1.2 Planting site

Properties of planting sites are highly diverse and are to a large extent determined by the former land use. However, all planting sites have in common that they were used more or less intensively by humans and thereby lost much or extensive parts of their ecological integrity and functionality and with that their capacity to provide services relevant for society. For example, forests can be degraded by overharvesting or poor management and agriculture land through poor practices that mine soil nutrients or result in excessive erosion (Verdone, 2015). In the context of reforestation, the properties of the intended area for restoration as well as the properties of the surrounding areas are equally important. The envisaged restoration transition is often constituted by the degrading land use practices. Verdon (2015) identified tree major restoration transitions:

Degraded agriculture → Agroforestry
Degraded woodlots and plantations → Woodlots with improved management
Bare land (deforested land) → Establishment of planted forests

Although these three transitions differ in their principles, when it comes to the planting of trees, the same question arises in all three cases: *What is the current predominant vegetation type on the intended area for restoration?* This question is crucial for the choice of planting material and in connection with that the necessary land preparation method and maintenance (Cole et al., 2011; Shoo & Catterall, 2013; Zahawi & Holl, 2009). Not all restoration projects and research trials explicitly name the vegetation type of the intended restoration site but most of them name the former land use, which gives an indication on the vegetation type. For abandoned pasture, for example, it can be assumed that the land is predominantly covered by grass and occasionally shrubs. Based on these considerations, we have identified the following planting site characteristics:

Abandoned pastures → Predominant vegetation consists primarily of grass species
Abandoned plantations → Predominant vegetation consists of trees, shrubs and grass species
Secondary forest → Predominant vegetation consists of trees and shrubs species

2.2 Variables

2.2.1 Germplasm

Trees and shrubs can be propagated from seeds or vegetatively. In most cases, restoration projects work directly with seeds (direct seeding or soil seedbank) or with material that have been propagated from seeds (seedlings from nurseries or widlings) (Gregorio et al., 2010; R. Jalonen et al., 2018). Vegetative germplasm, on the other hand, are used much less common (R. Jalonen et al., 2018), although they offer some significant advantages. One of them is that vegetative organs are in general not only much larger than seeds, and in some cases even larger than seedlings, but also contain greater reserves of energy. This helps the germplasm to grow more rapidely and thus to become faster competitive for light, water, and nutrients, which ultimately helps the planting material to better establish in dense plant communities such as grasland (Forbes, Forbes, & Watson, 1992). In terms of costs, this means that less land preparation is needed when planting material propagated vegetatively (Kuaraksa & Elliott, 2013; Zahawi & Holl, 2009). The most common methods of artificial vegetative propagation for restoration are cutting, grafting, layering, tissue cultures and stakes (Graudal & Lillesø, 2007; Kuaraksa & Elliott, 2013). However, Layering, grafting, and tissue culture are only limited suitable for mass propagation, especially in developing countries because of its high costs and the need for technical expertise (Kuaraksa & Elliott, 2013). More common are stakes and cuttings whereby stakes are also cuttings but with a height of 2m usually bigger than what is normally understood as cuttings, such as freshly cut lateral branches with a length of about 10-20cm (Kuaraksa & Elliott, 2013; Zahawi & Holl, 2009). Furthermore, vegetative stakes are often used as live fences in the tropics (Zahawi & Holl, 2009).

2.2.2 Planting material

Planting nursery-raised tree seedlings is the most often used method to restore degraded tropical landscapes (Bozzano et al., 2014; Lamb, Erskine, & Parrotta, 2005; Schmidt, 2008; Zahawi & Holl, 2009). With seedling survival rates of more than 80% this popularity is not surprising (Zahawi & Holl, 2009). In the study of Jalonen et al. (2018), almost two third of the surveyed forest restoration projects stated that they primarily use nursery-raised tree seedlings for their restoration efforts. This method, however, is also one of the more expensive approaches to restoring degraded landscapes (Cole et al., 2011; Kuaraksa & Elliott, 2013; Zahawi & Holl, 2009).

In contrast, the least costly method to restore forests is supposedly through natural regeneration (Chazdon, 2003; Lamb et al., 2005). Yet, as for all other methods, socioeconomic circumstances, as well as the ecological situation, such as the state of degradation, ultimately determine whether natural regeneration is feasible and hence leads to success or not (Chazdon, 2003). For example, natural regeneration is only possible if natural forest remnants and with that suitable germplasm with sufficient genetic diversity are present in the surrounding landscape. Possibly because of this or because natural regeneration needs more time than other approaches, only six percent of the restoration programmes surveyed by Jalonen et al. (2018) relied on natural regeneration as a method.

Besides natural regeneration, direct seeding is also a more cost-effective method compared to planting nursery-raised tree seedlings (Cole et al., 2011; Grossnickle & Ivetić, 2017; Zahawi & Holl, 2009). However, the overall performance of direct seeding is lower compared to that of planting seedlings. Only about 20% of the seeds planted normally survive, mostly due to difficult site conditions, seed predation and vegetation competition (Grossnickle & Ivetić, 2017; Schmidt, 2008). Nevertheless, there is an increasing interest in direct seeding as an alternative to planting seedlings (Madsen & Lof, 2005). Currently, however, Jalonen et al. (2018) shows that the method is the prevalent method in about nine percent of the examined restoration projects. In addition to the favourable economic aspects, it is the ecological advantages that makes direct seeding promising. For example, with direct seeding a very large variety of species can be achieved (Ammer, Mosandl, & El Kateb, 2002; Schmidt, 2008). Furthermore, the resulting plant communities have a denser and larger root system (Schmidt, 2008).

The method of planting vegetative propagules have received even less attention than direct seeding, although this method has some striking advantages (Zahawi & Holl, 2009). For example, stakes grow much faster than seedlings and therefore may provide rapid erosion control and a sufficient competitive edge against shorter pasture gras (Zahawi & Holl, 2009). Like stakes, wildlings also have the advantages that they do not require a nursery and therefore are more cost effective than nursery raised seedlings. Parrota and Knowles (2001) stated that for their project, planting wildlings, which were collected from the surrounding old grown forests, was for some species the most cost-effective planting stock option.

2.3 Actors

The motives for restoration are manifold and accordingly the group of actors involved in restoration projects is diverse. Lamb et al. (2005) name three major motives for restoration, which are considered a response to the process of forest degradation and land use change, and the adverse effects that come with it: (1) The expansion of protected areas or the network connecting these areas, (2) the improvement of agricultural productivity, and (3) some form of reforestation. These categories fit well with the purposes for landscape restoration named in various publications (see e.g. (Bozzano et al., 2014; R. Jalonen et al., 2018; Mansourian & Vallauri, 2005). The resulting initiatives may have their origin on a supranational level leading to restoration endeavours on a large scale, such as the Billion Tree Campaign (2006) or the Bonn Challenge (2011). They can also originate on a national or regional level, e.g. Green Wall of China (1978) or The Green Mission in India (2010), or on a community or even individual level. Thus, the actors involved differ significantly according to the nature of the initiatives. Lars Graudal & Lillesø (2007) provide a timeline of major development and practices for tree seed production and along with that how actors in restoration have changed over time. According to their timeline, the underlying driver for seed production changed over time from primarily commercial driven objectives, where national public seed production centres provided seeds for the improvement of plantation programmes, to the aim of supporting rural house-holds needs and smallscale agriculture, and the conservation of biodiversity. In many contexts, NGOs have taken over the role that was originally assigned to national tree seed sentres in the course of this development and hence donor support shifted accordingly (Graudal & Lillesø, 2007).

In the following, we identified the main actors along the tree supply system. By doing that, we are well aware that for each context the system and with that the actors and the extent to which each of them is engaged in the supply of trees may change significantly. In general, Graudal & Lillesø (2007) pointed out that a supply system can be organised centralized or decentralized. On the one hand, in very centralized systems, as it is often the characteristic for national tree seed programmes or large NGOs, the project staff is normally involved in all activities along the supply system (Graudal & Lillesø, 2007). On the other hand, in decentralized systems, which are more common in small-scale enterprises or in the non-commercial diffusion between farmers, much of the work is outsourced to local labourers or is done independently by the farmer themselves (Graudal & Lillesø, 2007).

2.3.1 Collectors and planters

Who collects and plant the seeds depends on different factors. Certainly, access to the source and land tenure play an important role. The organizational structure of the project might also be a decisive aspect. In centralized projects, seeds are normally collected and/or planted by own staff. The majority of practitioners (55%), who participated in the survey conducted by Jalonen et al. (2018), stated that collection by project staff was the most common seed acquisition strategy in the projects they have been involved. However, in order to reduce costs, centralised organisations do also hire local labour, instead of using own staff (Graudal & Lillesø, 2007). In the non-commercial sectors, collectors and planters are often the same person and act either independently or in more or less defined groups. In some cases, individual collectors and groups have joined together to form formalised networks, such as the Xingu Seed Network (XSN). Often these networks pursue similar goals. Foremost, they want to generate income for indigenous communities and smallholders by serving the growing demand for seed. An essential part of these efforts is the training for seed collectors and, in some cases, for planters. Moreover, the preservation of forests, and local cultures values is another motivation of these networks. In some cases, especially but not only in projects were academic or research organizations act as project leaders, researcher themselves collect seeds (R. Jalonen et al., 2018).

2.3.2 Nurseries

Nurseries can either be owned and/or run by local communities (e.g. local farmers, villagers, etc.), by governmental bodies, by NGO's, or jointly by aforementioned actors. Dedefo (2017) showed that a majority of the nurseries in Ethiopia (62.5 %) is governmental owned and run. Half of the remaining nurseries in Ethiopia are run by NGO's and farmers respectively (Dedefo et al., 2017). Roshetko et al. (2018) too, showed that a majority of the examined nurseries, of which all were located in tropical and subtropical areas around the globe, are neither fully nor partially owned and run by local communities (62%). Tripp and Rohrbach (2001) provide a possible explanation for this ratio. According to their study, which is focussing on Sub-Saharan Africa, not only regulatory frameworks are hampering private businesses at community level but also market distortions caused by the free or heavily subsidised provisioning of seeds by government or NGO (Tripp & Rohrbach, 2001).

2.3.3 Normative actors

Normative actors set standards and provide guidance (Graudal & Lillesø, 2007). This includes the development of policies, regulating mechanisms, and dissemination of information and training programmes that ensure optimal market conditions, as well as the use of the most pertinent technique and species'mix for a sustainable and effective achievement of restoration goals. We foremost see governmental bodies, international development and public agencies, such as FAO, ICRAF, or IUCN, NGOs, and academic or research organisations, such as Bioversity, in the role of normative actors. However, in the long run, it would be desireable that actors along the seed supply chain, such as collector's networks, nurseries, or planters themselves take over the role of a normative actor and with that guaranty the compliance with standards as well as continuously improve them and the associated guidlines.

3. Costs in Tree Supply Systems

In a next step, we have identified major activities and methods as well as cost pools of the system and complemented the system picture accordingly (Figure 2). The cost pools ultimately indicate where in the system the cost-determining factors merge. All of the identified cost pools are composed of a combination of the following four cost components: Labour, transportation, equipment, and storage. These cost components in turn can be made up from different cost units. Labour costs, for example, may consist of gross earnings of locally hired nursery workers and of the administrative staff. In this way, labour costs includeds both the costs directly associated with the development of nursery crops, such as sowing seeds or irrigating seedlings, as well as indirect costs, such as administration or marketing. Apart from that, cost components may also vary in amount because they also depend on the choice of methods which, in turn, decisively depends on the properties of the system (resources and variables) and the expected quality requirements. For example, planting seeds on sites covered by pasture grasses requires substantially more preparation work and a more intensive use of herbicides than sites with no grass covering (Cole et al., 2011; Shoo & Catterall, 2013). Or, more labour- and equipment-intensive collection methods are necessary to avoid collecting seeds affected by fungy or deseases compared to methods, which do not focus on these quality requirements (Gregorio et al., 2010; L. Schmidt, 2000). In addition, these cost components are also influenced by factors that are not directly related to the properties of the system. For example, labour costs are also depending on the local wage level. Most of the studies we examined calculated wage costs at an hourly rate of arround US$ 1. Kuaraksa & Elliott (2013), for example, used a rate of US$ 0.82 per hour to calculate labor expenses or their field experiments in Thailand. For Costa Rica, Zahawi & Holl (2009) calculated using US$ 1 per hour and with that used a similare rate. While this rate is somewhat similar for developing countries, higher labour costs must of course be taken into consideration for industrialized countries. In addition to regional differences, wages also depend to a large extent on the qualifications of the workforce. Nevertheless, for the sake of clarity and simplicity, we have refrained from further specification. Despite this simplification, a unit is available to calculate labour expenses, while project descriptions or method sections of field experiments do not specify a uniform unit to calculate material, storage or transportation costs, such as US$ per driving kilometre.

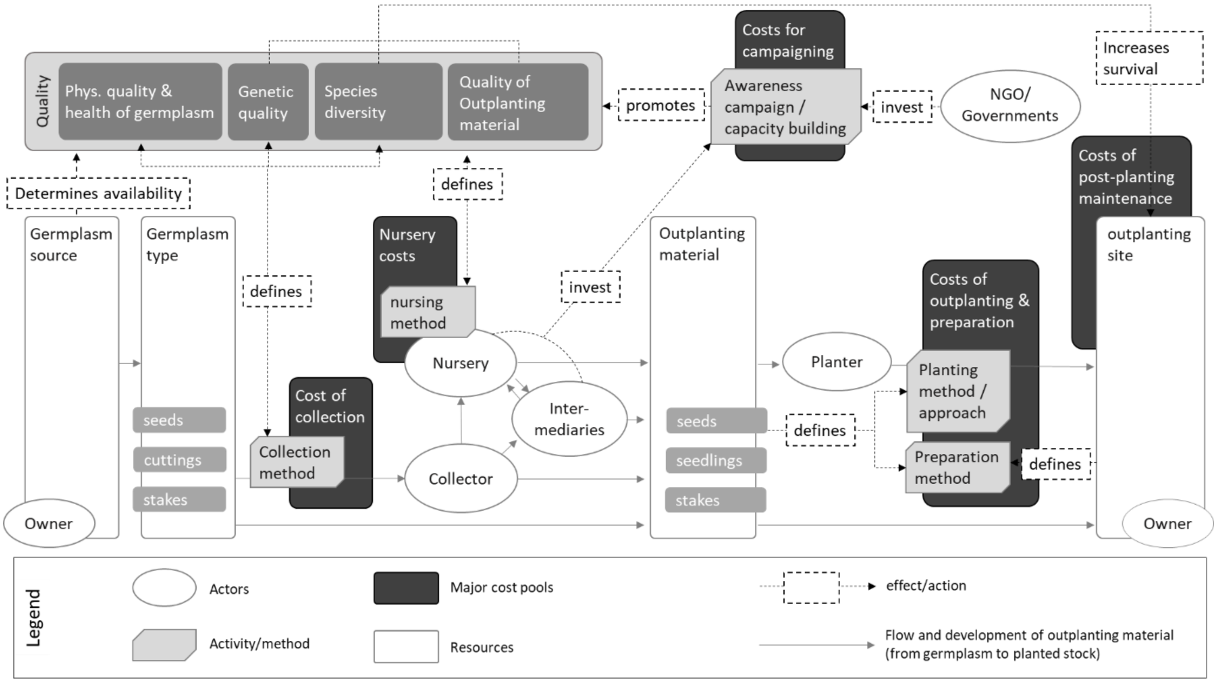

Figure 2: Tree seed and seedling supply system with key components and main cost pools of and interrelations within currently applied seed sourcing strategies.

In the following, we briefly explain what we mean by quality in connection with this report. After that, we describe how the choice of seed collection methods is determined or at least influenced by properties of the system and in particular by quality requirements. For each cost pool we discuss separately which factors are decisive for the choice of the method and afterwards how this might influence the costs.

3.1 Quality

For the description of quality, we refer to the definition given by FAO that determines between four basic quality attributes: Physical qualities, physiological qualities, genetic quality and seed/seedling health (FAO, 2016). According to this definition, physical quality relates to the condition of the seed or seedling in a specific seed lot (moisture content, presence of other seeds, etc.). Seed and seedling health refer to the presence of pests and diseases . Physiological quality is reflected in the maturity, viability and vigour of a plant and is ultimately referring to the tree's performance. These parameters, in turn, depend on a number of (agronomic) components, such as the development of the root system or the carbohydrate reserves. Finally, the genetic quality of the planting material is reflected in the inherited growth potential, which depends on the genetic quality of the parent trees and/or on the genetic variation within the source population. While physiological quality of seeds has great impact on the germination rate and the quality of seedlings and with that has a direct influence on the establishment success and the immediate survival of the planting stock, the genetic quality is decisive for the success of the restoration both in the short and long term (Alfaro et al., 2014; L. Schmidt, 2000; Tanaka, 1984; Thomas et al., 2014). A broad genetic diversity, for example, is essential for tree species to adapt to changing conditions and is a vital prerequisite for the long-term viability in the replanted population (Mortlock, 1999; Thomas et al., 2014).

In addition to these four basic quality attributes, we do also consider the plant diversity as quality attribute. We equate plant diversity with species richness (number of different species) and functional diversity[1]. There is a growing consensus that especially functional diversity has a crucial effect on ecosystem resource dynamics and the long-term ecosystem stability (Díaz & Cabido, 2001).

3.2 The cost of collection

Although many authors discuss costs in connection with collection methods, their explanations are mostly limited to qualitative descriptions. We have found only two studies (Cole et al. (2011) and Zahawi & Holl (2009)), which explicitly mention the collection costs in connection with their field experiment and thereby provide qualitative information (Table 1). In both studies the share of collection costs in the total costs of tree supply varies between 1% and 25%. Part of this range is due to differences between different types of germplasm whose collection causes different costs (see section 3.2.2). However, the main part of the range is explained by the subsequent cost pools, such as the planting and land preparation costs or the post-maintenance costs, which may also vary greatly in their amount depending on the characteristics of the system or on different planting methods (more details in the chapters 3.3 – 3.5).

Table 1: Collection costs per hectare with a tree density of 1500 ha^{-1} in US$. The table furthermore shows characteristics of the tree seed and seedling supply system that might have an impact on costs.

Germplasm source (distance to nursery)	**Phys. Q. & health**	**Genetic quality**	**Species diversity**	**Germplasm type**	**Country**	**Cost ha^{-1}**	**Labour costs** hr^{-1}	**Author, Source**
3 sp.: < 10 km radius 2 sp.: ~ 25 km away	Collect from ground or tree	4 widely separated trees	5	Seeds	Brazil	**\$15 – \$45**	\$ 1	(Cole et al., 2011)
9 sp.: < 3 km radius 1 species: N/A	N/A	N/A	10	Seeds	Costa Rica	**\$23 – \$30**	\$ 1	(Zahawi & Holl, 2009)
9 sp.: < 3 km radius 1 sp.: N/A	N/A	N/A	10	Stakes	Costa Rica	**\$180 – \$240**	\$ 1	(Zahawi & Holl, 2009)

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[1] For functional diversity, we refer the definition provided by Díaz & Cabido (2001): “The value and range of functional traits of the organisms present in a given ecosystem. The value of traits refers to the presence and relative abundance of certain values (or kinds) of leaf size, nitrogen content, canopy heights, seed dispersal and dormancy characteristics, vegetative and reproductive phenology, etc.”

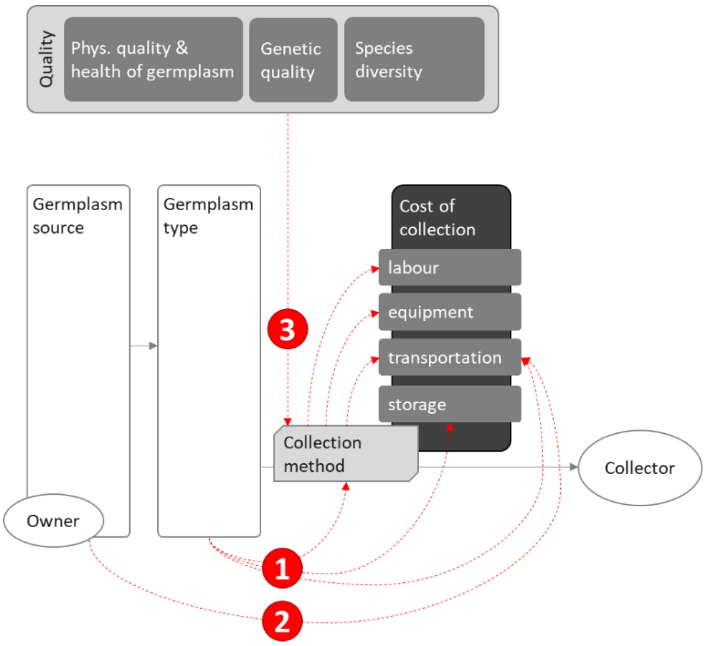

Figure 3: Components of the collection costs with the most important influencing factors.

The costs of collection consist mainly of labour costs, equipment costs, transport costs, and storage costs (Figure 3). These costs components are primarily influenced by the collection method, which in turn is determined by the type of germplasm and the quality requirements. Furthermore, the type of germplasm as well as the source of germplasm may also affect the transportation and storage costs directly. In the following, we first discuss the share of each cost components in the total collection costs. We then describe how the type of germplasm affects the costs either directly or indirectly by being decisive for the choice of methods (No. 1 in Figure 3). In a next step, we describe how the source of germplasm may affect the costs of collection directly. (No. 2 in Figure 3). Finally, we describe how the quality requirements and the species diversity indirectly influence the costs, by being, like the type of germplasm, decisive for the choice of collection methods (No. 3 in Figure 3).

3.2.1 Share of each cost components in the total costs of collection

None of the reviewed literature provides information which would allow to either directly or indirectly quantify the share of the various cost components in the total costs of collection. Therefore, the proportions provided in Table 2 are estimates based on qualitative considerations which essentially refer to the differences between the cost components and the total costs between the type of germplasm (see section 3.2.2 and Tables 3 and 4). According to this data, the share of each cost components varies significantly between different types of germplasm (Table 2). We have not found a study that reported the costs for collecting cuttings. Therefore, our assessment of the composition of the total cost of collecting cuttings is based on the qualitative weighting of the impact of possible cost drivers on the four main cost components in comparison to the other two types of germplasm. (Table 3).

Table 2: Share of each cost components in total costs of collection. A yellow colouring of a box indicates that the value in this box is an estimate and that it is mainly based on qualitative data and only partially on quantitative data. A red colouring indicates that the value in this box is only based on qualitative data. For values in boxes with a colour other than green, very little data was available for quantification.

Cost component	**Collection of seeds**	**Collection of stakes**	**Collection of cuttings**
Labour	56%	24%	47%
Tools and equipment	19%	1%	12%
Transportation	11%	65%	18%
Storage	15%	10%	24%

3.2.2 The impact of the type of germplasm on collection costs

The type of germplasm is decisive for the choice of the collection methods and hence for the effort and equipment that is needed for collection. Beyond this the propagation strategy of the species itself also determines how seeds can or should be collected (see also section 3.2.4). Many different collection methods are available for matching the respective plant propagation strategy or the characteristics of a certain type of germplasm. They range from simple collection from the ground to more elaborate methods such as climbing trees or the use of expensive and sophisticated equipment. These methods have been described in detail by various authors and principles and recommendations were made available to practitioners in a variety of guidelines (e.g. Schmidt (2000), Mwitwa (1990), FAO (1993), Guarino, Ramanatha Rao, & Goldenberg (2011), Mortlock (1999), Mulawarman et al., (2003), see also section 3.2.4).

Because of the inter-species variation in collection methods, it is difficult to quote universal costs for the collection of a specific type of germplasm. A look at the pricing of seeds illustrates these difficulties. For example, the price per kilo of cheaper typically big seeds and the more hard to get and therefore more expensive seeds offered by the Brazilian Xingu Seed Network roughly differ by a factor of 250, with an average of US$15 kg^{-1} (Campos-Filho, Da Costa, De Sousa, & Junqueira, 2013; Xingu Seed Network, 2013). Nevertheless, we found it pertinent for the sake of simplicity to define average costs for collecting instead of further segregating the costs. We base this approach on the assumption that the selection of species for a restoration project will most likely include both the more expensive and the less expensive species, thus offsetting the most extreme values.

The majority of the available literature is mainly focussing on collecting seeds but not on collecting other type of germplasm, such as stakes or wildings. However, many aspects relevant to the collection of seeds are also somehow relevant to the collection of other types of germplasm.

Only the study of Zahawi & Holl (2009) explicitly mentioned and compared the collection costs of two different types of germplasm. Their study revealed that the collection costs of stakes for a field experiment in Costa Rica were approximately seven times higher than the costs of collecting seeds for the same experiment (Zahawi & Holl, 2009). Such a direct comparison within the same study can be regarded as particular informative as it can be assumed that the underlying parameters are identical. The only other study that explicitly reported the collection costs, though without comparing different type of germplasm, was conducted by Cole et al. (2011). The cost for collecting seeds for their trial in Brazil was of the same magnitude as the costs reported by Zahawi & Holl (2009) (Table 1).

Some of these costs can be attributed to different transportation costs. Transportation of seeds from the collection site to the nursery is generally easier and cheaper than the transportation of stakes. This is mainly because a typical pickup truck can carry approximately 125 times the number of seeds as stakes (Campos-Filho et al., 2013; Zahawi & Holl, 2009). However, this is only an average order of magnitude. Of course, this factor varies considerably depending on the size and shape of stakes and seeds. Besides this, stakes may also suffer damage during transportation to the cortical tissue along the stem caused from excessive shaking if not placed properly, which also takes up more space compared to arbitrary placing (Zahawi & Holl, 2009).

In addition to differences in transport, the amount of work required to collect different germplasms may also differ. Although seeds can be collected much faster in larger numbers than stakes, they are not always available because of their high interannual variability (Zahawi & Holl, 2009). Stakes on the other hand, are almost always available since in many areas of the tropics some species are widely planted as fencerows (Zahawi & Holl, 2009). These statements are again to be understood as rough tendencies. Their underlying assumptions may not be valid for all cases. In restoration projects that aim for a high species diversity, for example, the availability of stakes is likely to become a limiting factor that may only be overcome by an increased collection effort. In such projects the collection of seeds might be the more cost-effective method.

Furthermore, higher material costs are to be expected when collecting seeds in comparison to collecting sticks. Often, especially in connection with quality considerations, seeds have to be picked directly from the tree, which is not only associated with more work but also with more expensive equipment.

In some cases, the collected germplasm has to be temporarily stored before it can be transferred to the nursery (Schmidt et al., 2018). In general, the associated costs are rather marginal compared to other cost components. However, because of different space requirements, storage costs may differ between different types of germplasm. Stakes, for example, need considerably more space than seeds.

In Table 3, we have listed the most important cost drivers which, in our opinion, lead to the fact that the collection of different type of germplasm is associated with different costs.

Table 3: A summary of possible cost drivers specific to a type of germplasm. The values are a rough qualitative weighting of the impact of a cost driver on the cost component of the respective type of germplasm. The colouring of the boxes is an indication for the robustness of the weighting. A green colouring indicates that the weighting is at least partially based on quantitative data. A yellow colouring indicates that the weighting is based on qualitative data. The weights in red boxes are assumptions.

Cost Comp.	Cost Drivers	**Seeds**		**Stakes**		**Cuttings**
Labour	Compared to stakes, the majority of seeds (*and cuttings*) can be collected relatively quickly.	0	<	+2	>	0
	In general, seeds (*and cuttings*) can be collected in much larger numbers than stakes.	0	<	+4	>	0
	Some seeds need to be collected from the treetop	+1	>	0	=	0
	High interannual variability in seed (not always available). In contrast some stakes are widely planted as live fencerows (high availability)	+1	>	0	<	+1
	Total	**2**	**=**	**6**	**=**	**1**
Tools and equipment	Some seeds are difficult to collect (only from treetop) and need special equipment (1/3 of the cases?)	+1	>	0	=	0
	Total	**1**	**>**	**0**	**=**	**0**
Transportation	Transportation of seeds is easier. A pickup truck can carry 125 times the number of seeds as stakes	0	<	+125	>	0
	Total	**0**	**>**	**125**	**>**	**0**
Storage	Stakes need more space than seeds	0	>	+5	**<**	**0**
	Total	0	>	5	**<**	**0**

Based on the defined shares of each cost component in total costs (Table 2), the above assumptions about the impact of the various cost drivers (Table 3), and costs reported by Zahawi & Holl (2009) and Cole et al. (2011) (Table 1, section 3.2) we have broken down the total costs into the respective four cost components (Table 4). The figures in Table 4 represent only basic costs, which means that they do not include any additional cost drivers (e.g. high genetic diversity or species richness) other than the ones discussed above. The effect of these cost drivers is discussed in the following sections. The total collection costs of each type of germplasm (Table 4) are therefore lower than the costs reported by the two authors (Table 1, section 3.2).

Table 4: Cost estimates (US$) to collect seeds, stakes, and cuttings. Costs are per 1500 individual seedlings

Cost components		**Costs for Seeds**			**Costs for stakes**			**Costs for cuttings**		
	Unit (USD)	ha^{-1}	Costs	%	ha^{-1}	Costs	%	ha^{-1}	Costs	%
Labour	$1.00/hr	15,0	15,00	56%	45,0	45,00	23%	8,0	8,00	47%
Equipment	$1,00	5,0	5,00	19%	2,0	2,00	1%	2,0	2,00	12%
Transportation	$1,00	3,0	3,00	11%	125,0	125,00	65%	3,0	3,00	18%
Storage	$1,00	4,0	4,00	15%	20,0	20,00	10%	4,0	4,00	24%
Total Collection C.			27	100%		192	100%		17	100%

3.2.3 The impact of the collection site on collection costs

Possible cost drivers related to the collection site are the distance between the collection site and the nursery as well as the access to the area where the mother trees are located, which might be impeded by difficult terrain or restricted accessibility for vehicles. In fact, many locations cannot be reached by vehicles and therefore the equipment has to be carried (L. Schmidt, 2000). We have developed three different indicators that can be used to assess the reachability of the source of germplasm (Table 5).

Table 5: Characteristics for the reachability of the collection site and associated indicators. Only characteristics are listed that have a potential major impact on the costs.

	Reachability of collection site		
	Easy reachable	Average reachable	Difficulty reachable
Distance of nursery/planting site	<10km radius of nursery/planting site	10km – 20km radius of nursery/planting site	> 20km radius of nursery/planting site
Distance from road	Besides roads	Near roads (< 1km)	Far from roads (> 1km)
Terrain	Even terrain	Uneven terrain	Impassable terrain

While the indicator distance to the nursery mainly influences the transportation costs, the accessibility indicators (distance from the road and terrain) mainly affects the time necessary to collect the desired quantity of seeds and with that has implications on the labour costs. Based on these considerations, we defined for each restriction of the reachability (from easy to average to difficult) for both cost components an equal linear cost increase of 25% of the costs that would be expected if the reachability were easy (Table 6).

Table 6: Effects of the reachability on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Transportation**	
Reachability of germplasm source	Easy reachable	-	1.00	-	1.00	-	1.00
	Aver. reachable	+	1.25	-	1.00	+	1.25
	Diff. reachable	+ +	1.50	-	1.00	+ +	1.50

3.2.4 The impact of quality considerations on collection costs

The choice of seed collection methods may have implications for the quality of the collected germplasm. To ensure an appropriate quality and a secure collection process without jeopardizing safety of staff or the integrity of mother trees with the smallest possible costs, several factors have to be considered (L. Schmidt, 2000). Despite that, in many cases only economic considerations are decisive for the choice of methods (L. Schmidt, 2000).

Ensuring physiological quality and seed health

Foremost, the characteristics of the species itself is pivotal for the choice of method and ultimately for the effort that is needed for collection. Whereas some species, for example, are bearing abundant and regular seeds crops, which remain on the tree for a long time, other species produce only small seed crops that are dispersed or fall directly to the ground shortly after maturity (L. Schmidt, 2000). Seeds from these species are more likely to get lost to predators or contaminated with bacteria and fungi that may damage the seeds (Gregorio et al., 2010; L. Schmidt, 2000). Hence, the right timing and method greatly affect the quality of the seeds.

According to Gregorio et al. (2010), it is best in any case to collect seeds before they fall from the trees because of the aforementioned reasons and because it is difficult to identify the mother tree where the seed comes from after it has fallen down. However, collecting seeds from the tree directly usually requires more labour and equipment which leads to higher costs. Whereas low branches can be reached from the ground, the collection from higher branches already need additional equipment like long-handled pruners or saws and the appropriate knowledge to use the equipment (L. Schmidt, 2000). For tall trees, where branches cannot be reached by long handled tools, climbing is necessary to reach the fruit bearing branches. A collection method that obviously implies the risk of fatal accidents. In order to minimalize the risk for collectors, not only appropriate equipment is needed but also the necessary expertise to use it. Hence, any collection that involves climbing is relatively equipment and knowledge intense as well as time consuming, which directly has an impact on the associated costs (L. Schmidt, 2000).

In contrast, collection from the ground is much less labour and equipment intensive as well as time consuming and, moreover, requires less skills (Doran, Turnbull, Boland, & Gunn, 1983; L. Schmidt, 2000). Whereas large seeds can efficiently be picked up directly from the ground, nets, funnels, or tarpaulins under the trees may help to increase the efficiency when collecting small seeds (Doran et al., 1983). Although this is associated with higher material costs, the yield is greater and thus the collection more efficient. The efficiency can be even increased by shaking the tree, if the constitution of the species so permits. Not only more seeds can be collected with this method than by awaiting natural fall, the loss to dispersal, ground predation, deterioration and germination can also be reduced (L. Schmidt, 2000).

In addition to the above mentioned methods, seeds can also be collected from fallen trees or by shooting down branches (L. Schmidt, 2000). However, these methods are rarer and only applicable in certain settings. Wildlings should be collected when they are still very young in order to preserve their physical integrity as far as possible and with that ensure a high physiological quality. At an advanced age, the root system is already widely developed and well anchored, which increases the chance of damaged when the plant is removed from the soil (Gregorio et al., 2010). This restriction may limit the availability of wildlings, which is likely to the search effort and thus the amount of work.

In addition, care should be taken to ensure that the seed is stored correctly. The quality of seeds can only be maintained under species-specific optimal storage conditions, e.g. humidity and temperature (Tanaka, 1984). Table 7 summarizes the characteristics of collection methods for two types of germplasm (seeds and stakes) that are decisive for the physiological quality and health of the germplasm.

Table 7: Quality categories (low, medium, and high) and associated collection methods with indicators. Only indicators are listed that potentially have a major impact on the physiological quality and the health of the germplasm as well as on the costs.

	Physiological quality and health of collected material		
	Low quality	Medium quality	High quality
Collection method (seeds)	- picked up from the ground - collection method unknown	- picked up from the ground and collected from the tree	- collected from the tree - use of equipment to prevent falling to the ground - appropriate storage facility (control environmental . conditions)
Collection method (stakes)	- collection of matured wildings with developed root system	- collection of matured and young wildlings	- collection of young wildlings

Based on the preceding elaborations, we have defined the effects of the three quality categories (low, medium, and high quality) on the three cost components (labour, equipment, and transportation) (Table 8). We defined for each tightening of requirements for the affected cost components (labour and equipment) an equal linear cost increase of 25% of the costs that would be expected with only low-quality requirements.

Table 8: Effects of quality categories on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Storage**	
Physiological quality and plant health	Low quality	-	1.00	-	1.00	-	1.00
	Medium quality	+	1.25	+	1.25	+	1.25
	High quality	+ +	1.50	+ +	1.50	+ +	1.50

Ensuring genetic quality

Provenance of the germplasm is another crucial factor not only in terms of costs but especially for the fitness of the seedlings. At least in the short and medium term or under the assumption that environmental conditions in a particular location is stable, the seeds of local mother plants provide the best conditions for a successful restoration project. Local plants are not only adapted to local conditions such as soil type, local plant communities, or climatic extremes (e.g. max. degrees of frost) but also are best integrated into the local ecosystem and thus also provide optimal habitat and/or interaction for the local fauna and flora (Mortlock, 1999). Hence, collecting seeds from naturally occurring remnant vegetation is usually the best approach (Mortlock, 1999). Several studies have shown that genetic differentiation between populations of the same species but from different regions can be highly significant. Loha et al. (2006), for example, showed that germination performances and height growth of a major timber species in Ethiopia differ significantly among provenances and that strong correlation between germination traits and certain local conditions most likely indicate and adaptation for seedling establishment. Based on literature review, Roshetko at al. (2018) showed that variation among provenance in growth and wood production of common trees of reforestation projects is by no means an isolated phenomenon but can be observed in many cases. However, according to Rogers & Montalvo (2004), proven examples of planting projects that have failed do to maladaptation are rare. As a reason for this the authors name the long period until perceptible signs of maladaptation show up, as well as the fact that a variety of factors could be responsible for the failure of a project and that it is therefore difficult to trace project failure back primarily or entirely to genetic reasons (Rogers & Montalvo, 2004). Furthermore, in some areas the conditions might have changed or will change considerably due to climate change or land use. In such cases, locally adapted plants may not always provide the best conditions for a successful project (Mulawarman et al., 2003).

Besides the region, the **type of source** might have another significant effect on the genetic constitution of the germplasm. While the genetic quality of germplasm from seed production areas, for example, is mostly known, it is often difficult to make a statement about the genetic quality if the germplasm derives from natural forests because history and ecology (selective harvesting, fragmentation, etc.) of these sites are not known in every case (Mulawarman et al., 2003). For example, years of targeted harvesting of certain species may led to highly fragmented and isolated relict populations. Depending on the degree of isolation and the propagation ecology of the targeted species and with that its ability to maintain genetic flow between populations, a reduced genetic diversity is to be expected in these populations due to increased levels of inbreeding and a greater impact of genetic drift (Furlan et al., 2012). Furthermore, habitat loss because of deforestation may also be an underlying cause for habitat fragmentation. Hence, the characteristics of the landscape surrounding the collection site also has to be taken into consideration. Whereas information of the past management practices of forests are scarce or difficult to access, more information is available for seed production areas, plantations or orchards. Furthermore, the **selection of the mother tree** greatly conditions the quality of seeds collected (Archer et al., 2014; Mulawarman et al., 2003; L. Schmidt, 2000). In order to ensure a suitable genetic quality, seed trees should be favoured that are in healthy and viable conditions. The underlying consideration is that most observable characteristics or traits exhibit some degree of heritability and hence the vitality and performance of progeny is determined not only by environmental conditions but also by the genotype of the mother tree (Mortlock, 1999; Mulawarman et al., 2003). The phenotype of the paternal tree cannot be directly evaluated simply because the source of pollen that pollinated the flowers of the seed tree are in most cases unknown. However, a conclusion on its condition can be drawn from the surrounding trees because most likely one of them is the source of pollen (Mulawarman et al., 2003). Similar quantities of seeds should be collected from several trees in order to avoid overrepresentation of a single individual (Mortlock, 1999).

In order to get an appropriate genetic diversity in the seed lot, seeds should be collected from a large number of trees. Depending on the author, the recommendations vary from at least 10 up to 100 unrelated trees (Jaenicke, 1999; Mortlock, 1999; Mulawarman et al., 2003; L. H. Schmidt, 2007; Sedgley, Hand, Smith, & Griffin, 1989). Furthermore, the collected seeds should all be from unrelated trees (Mortlock, 1999). Although this is difficult for many reasons, there are some basic principles. First, the risk of kinship decreases with an increasing distance between mother trees (Kitzmiller, 1990; Mortlock, 1999; Mulawarman et al., 2003; L. H. Schmidt, 2007). Therefore, seeds should be collected from trees spaced at least at a distance greater than that associated with seed dispersal, which means for wind dispersed species at least 50 to 100 metres and for animal a bit less (Kindt et al., 2005; Mortlock, 1999; L. H. Schmidt, 2007). Second, collection from too isolated trees should be avoided since the trees may be inbred or produce seed by inbreeding (selfing or self-pollination) which, as a consequence, may result in reduced fitness of progeny (Eckert et al., 2010; Kindt et al., 2005; Mulawarman et al., 2003).

Another factor that may influence the quality of collected seeds is the **number of harvesting events**. According to Kettle et al. (2008), not all trees in a population are necessarily reproductively active at the same time. Therefore, if the harvest is limited to one season only, there is a risk that the sample will not contain the genetic diversity of the entire population (C. J. Kettle et al., 2008)

Table 9 summarizes the characteristics of collection methods for all types of germplasm that are decisive for the genetic quality of the germplasm. These characteristics can be used at the same time as indicators for determining which quality requirements (low, medium, high) can be met if the corresponding condition is given.

Table 9: Quality categories (low, medium, and high) and associated collection methods with indicators. Only indicators are listed that potentially have a major impact on the genetic quality as well as on the costs.

	Genetic Quality		
	low genetic quality	medium genetic quality	high genetic quality
land use	- plantation or farmland with unknown genetic quality or genetically homogenous trees - isolated forest fragments	- Managed medium-sized forest	- Large-scale primary forest - Seed Orchards
Distance between mother trees	- Neighbouring trees - Isolated trees	< 75m	> 75m but not isolated
No. of mother trees	< 10 trees	10-50 trees	> 50 trees
No. of harvesting seasons	1	> 1	> 1

In Table 10, we have defined the effects of the three quality categories (low, medium, and high) on the three cost components (labour, equipment, and transportation). We defined for each increase in quality for both affected cost components (labour and transportation) an equal linear cost increase of 25% of the costs, which would be to be expected if no or only very low quality were pursued.

Table 10: Effects of quality categories on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Transportation**	
genetic quality	low quality	-	1.00	-	1.00	-	1.00
	medium quality	+	1.25	-	1.00	+	1.25
	high quality	+ +	1.50	-	1.00	+ +	1.50

Species diversity

According to Roshetko et al. (2018), many practitioners neglect to appropriately consider species diversity in their projects. Not even half of the afforestation/reforestation project plans, which have been examined by the authors intended to plant more than five species (Roshetko et al., 2018). According to Schmidt (2007), it is above all economic considerations that lead to keeping the diversity of species low.

In the context of this cost analysis, two questions are of central importance: How many species are needed to achieve an optimal diversity? And, does a high number of species automatically mean a high functional diversity? While the first question cannot be answered universally because this can vary greatly from ecosystem to ecosystem, no universal answer is possible for the second question either. Díaz & Cabido (2001) are pointing out that such a correlation (high species richness equals high functional diversity) would only apply to specific theoretical cases and that such cases are not common in nature. We believe, however, that this simplification serves its purpose in terms of cost. Nevertheless, the benchmarks given in Table 11 are only an indication, which are essentially based on the ordered distribution (tertile) of the species richness considered in the 38 projects reviewed by Roshetko et al. (2018).

Table 11: Diversity categories (low, medium, and high) and associated indicators.

	Species Diversity		
	low species diversity	medium species diversity	high species diversity
Number of species	< 5 species	5 – 10 species	> 10 species

None of the authors discusses in detail where any additional costs would arise as a result of taking species diversity into account. However, as the number of species increases, so does the diversity of characteristics of species (shape and height of trees, types of fruits, fruiting process, density of individuals) which most likely necessitate the use of a wider range of collection methods. Furthermore, the search effort may also increase with the increase in species diversity as the chance increases that some of these targeted species might be not common or rare. Overall, we therefore assume that the consideration of species diversity in restoration projects tends to increase both labour and equipment costs.

We defined for each increase in diversity for both affected cost components (labour and equipment) an equal linear cost increase of 25% of the costs, which would be to be expected if only seeds are collected from five species or below.

Table 12: Effects of species diversity on the cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Transportation**	
Species diversity	low species diversity	-	1.00	-	1.00	-	1.00
	medium species diversity	+	1.25	+	1.25	-	1.00
	high species diversity	+ +	1.50	+ +	1.50	-	1.00

3.3 Cost of nursery

There are quite a few authors that have discussed costs associated with plant propagation in connection with guidelines and method descriptions. However, as with collection costs, respective statements are mostly qualitative in nature. We have found four studies (Campos-Filho et al. (2013), Cole et al. (2011), (2013) and Zahawi & Holl (2009)) that provide qualitative information on nursery costs associated with their field trials (Table 13). These costs can only be compared to a limited extent because some of the underlying parameters, such as labour costs, are either different or unknown. As far as possible, we have standardized these parameters. However, this was not possible for all parameters, which is why some uncertainties remain with regard to comparability.

For the propagation of seedlings, the share of nursery costs in the total costs of tree supply varies between 10% and 21%. The main part of the range is explained by the preceding collection costs and the subsequent cost pools related to planting and land preparation as well as post-maintenance costs. All these cost pools may vary greatly depending on the configuration of the influencing system components and thus also their share of the total costs changes. The share of costs associated with propagating cuttings in total costs is with 42% significantly higher but as well depends on the preceding and subsequent cost pools.

Table 13: Nursery costs per hectare with a tree density of 1500 ha^{-1} in US\$. The table furthermore shows characteristics of the tree seed and seedling supply system which might have an impact on costs.

No. of species	**Type of germplasm**	**Country**	**Cost ha^{-1}** *Density 1500 ha^{-1}*	**Labour costs US\$**	**Author, Source**
5	Seeds	Brazil	**\$225 – \$375**	1 hr^{-1}	(Cole et al., 2011)
47	Seeds	Brazil	**~\$470** *(\$1470[2])*	N/A	(Campos-Filho et al., 2013)
10	Seeds	Costa Rica	**\$225 – \$375**	1 hr^{-1}	(Zahawi & Holl, 2009)
6	Seeds	Thailand	**\$218** [1] (wage adjusted)	0.82 hr^{-1}	(Kuaraksa & Elliott, 2013)
6	Cuttings	Thailand	**\$552**[1] (wage adjusted)	0.82 hr^{-1}	(Kuaraksa & Elliott, 2013)

[1] Includes nursery materials (containers, media, fertilizer and rooting hormone) \$0.03 per plant (seed) \$0.04 per plant (cutting) + labour cost in nursery \$0.14 (seed) / \$0.40 (cutting); [2] Includes costs for seeds (approx. \$1000 ha^{-1} – calculated from the seed price of the seeds for direct seeding in the same project)

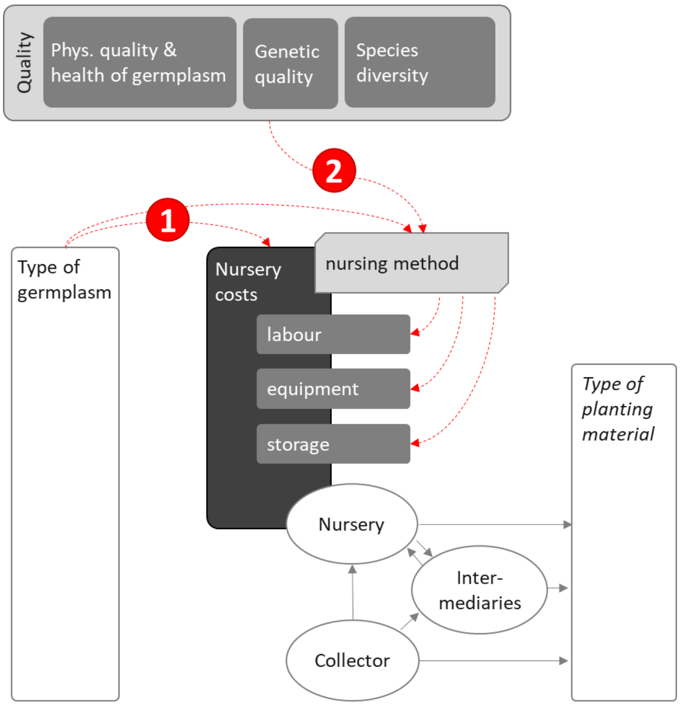

Figure 4: Components of the nursery costs with the most important influencing factors.

The costs of the nursery consist mainly of labour costs, equipment costs and storage costs (Figure 4). Equipment costs include all materials needed for the propagation and growth of the plants, such as containers, medium, fertilizer, hormones etc. They do not include the material needed for the establishment of the nursery. The costs associated with setting up a nursery must be added separately to the total costs. The study of Roshetko et al. (2018) showed that about one third of the reviewed projects set up a nursery specifically to serve the project planting need.

Labour costs include not only the direct cost associated with the production of seedlings but also costs associated with running a nursery, such as time and labour of administration, customer relations, marketing etc. cost pools are primarily influenced by the nursing method, which in turn is determined by the quality requirements. Furthermore, the type of germplasm (seeds or cuttings) may also affect the cost of the nursery either directly or indirectly. In the following, we first discuss the share of each cost components in the total nursery costs. We then describe how the type of germplasm may has implications on nursery costs by being decisive for the choice of methods (No. 1 in Figure 4). In a next step, we describe how the quality requirements and the targeted species diversity indirectly influence the costs, by being, like the type of germplasm, decisive for the choice of nursing methods (No. 2 in Figure 4).

3.3.1 Share of each cost components in the total costs of nursery

Only Kuaraksa & Elliot (2013) explicitly recorded data on the composition of the tree nursery costs. We used his data as a starting point for defining the proportion of the two cost components (Table 14). Accordingly, the share of labour costs and equipment costs in the total costs of nursery for planting material raised from seeds and cuttings are in the same order of magnitude. The difference of about 10% is due to the increased effort for propagating via cuttings versus seeds.

Table 14: Share of each cost components in total nursing costs. A yellow colouring of a box indicates that the value in this box is an estimate and that it is mainly based on qualitative data and only partially on quantitative data.

Cost component	**Nursing of seeds**	**Nursing of cuttings**
Labour	77%	87%
Tools and equipment	21%	12%
Storage	2%	1%

3.3.2 The impact of the type of germplasm on nursery costs

The type of germplasm is primarily decisive for what working steps are necessary for the development of outplanting material and accordingly how much labour and equipment is needed. That, of course, only applies to those types of germplasm that need nursery facilities to propagate and grow before they can be planted in the field, such as cuttings and seeds. Wildlings and stakes, on the other hand, might be planted directly after harvesting and do not require nursing facilities (Bonner & Karrfalt, 2008; Zahawi & Holl, 2009).

Like the collection methods, the nursing methods and approaches have been described in details by various authors and principles and recommendations were made available to practitioners in a variety of guidelines (e.g.

Bonner et al. (2008), Landis (1989), Schmidt (2000), Jaenicke (1999), FAO (1993), Gregorio et al. (2010), Wilkinson et al (Kim M Wilkinson, Landis, Haase, Daley, & Dumroese, 2014), see also section 3.3.3). In the following, we are focussing only on the most relevant aspects. For more detailed information on this topic, please refer to the references listed above.

Propagating planting stock from cuttings involves considerably more working steps than the propagation from seeds. In the case of seeds, it is often sufficient to sow them directly into containers or seedbeds with some type of artificial growing medium or an appropriate soil type (Bonner & Karrfalt, 2008; Kuaraksa & Elliott, 2013). In some cases, however, pre-treatments may be necessary to overcome the seed dormancy and to accelerate the start of germination (Jaenicke, 1999; Mulawarman et al., 2003; Schmidt, 2000). Once the plants have matured sufficiently, they are pricked out of the germination medium and potted into new containers (Jaenicke, 1999). There are also more elaborate methods where, for example, seeds are first pregerminated and then resulting sprouts are sowed into containers (Bonner & Karrfalt, 2008).

Cuttings, on the other hand, require several treatment steps. First, the cut surface needs a treatment to prevent bacterial infection (Kuaraksa & Elliott, 2013). After that, the root growth needs to be triggered and accelerated with hormones before they can be planted into containers (Bonner & Karrfalt, 2008; Kuaraksa & Elliott, 2013).

After seeds have germinated and matured to seedlings and cuttings have established, the treatment steps are similar and essentially aim the accustoming of the plant material to the field conditions and at the same time ensuring the vitality and quality of the plants.

Although the methods of reproducing cuttings are constantly being improved and with that become more efficient and cost effective, the associated costs are still higher than those of seedling production (Greenwood, Foster, & Amerson, 1991).

In some cases, it is necessary to store seedlings for the period from when seedlings are lifted until they are transported to the planting site. The type of storage depends on the species and the duration of storage. Cool storage is particularly suitable for maintaining the quality of seedlings (Bonner & Karrfalt, 2008). Where this is not possible, seeds can be stored for a short time in outside beds until they can be outplanted. Which methods to choose depends on the one hand on their availability and on the other hand on the characteristics of the plant species. Since our calculations do not consider either characteristics of different species or the availability, we add the same fixed amount as costs for store seedlings. These costs also include costs for any storage of seeds or cuttings before sowing or planting them into containers or seedbeds.

Table 15: A summary of possible cost drivers specific to a type of germplasm. The values are a rough qualitative weighting of the impact of a cost driver on the cost component of the respective type of germplasm. The colouring of the boxes is an indication for the robustness of the weighting. The yellow colouring indicates that the weighting is based on qualitative data.

Cost Comp.	Cost Drivers	**Seeds**		**Cuttings**
Labour	Seeds: Pre-treatments may be necessary to overcome the seed dormancy and to accelerate the start of germination	+1	>	0
	Cuttings: Treatment of the cut surface	0	<	+1
	Cuttings: Trigger and accelerate root growth	0	<	+1
	Total	**1**	**<**	**2**
Tools and equipment	Hormones	0	<	+1
	Total	**0**	**<**	**1**
Storage	Stakes need more space than seeds	0	=	0
	Total	0	=	0

Based on the defined shares of each cost component in total costs (Table 14), the above assumptions about the impact of the various cost drivers (Table 15), and costs reported by Kuaraksa & Elliott (2013) (Table 13, section 3.3) we have broken down the total costs into the respective four cost components (Table 16). The figures in Table 16 represent only basic costs, which means that they do not include quality requirements which may cause additional costs. The effect of these cost drivers is discussed in the following sections. The total collection costs of each type of germplasm in Table 16 are therefore lower than the costs reported by the two authors (Table 13, section 4.3).

Table 16: Cost estimates (US$) for propagation in a nursery. Costs are per 1500 individual.

		Costs for Seeds			**Costs for cuttings**		
	Unit	ha^{-1}	Costs	%	ha^{-1}	Costs	%
Labour	$1.00/hr	180	$180,00	77%	440	$440,00	87%
Equipment	$1,00	50	$50,00	21%	60	$60,00	12%
Storage	S1.00	5	$5,00	2%	5	$5,00	1%
Total collection cost			$235	100%		$505	100%

3.3.3 The impact of quality considerations on nursery costs

Seedling quality can be equated with the performance of the seedling on the outplanting site (Bonner & Karrfalt, 2008). This performance includes both the initial and long-term survival rate as well as the growth rate. Thereby, the appearance of the plant may be an indicator for its quality, but when viewed on its own, it is only limited meaningful (Kim M. Wilkinson & Douglas, 2014). Ultimately, it is the conditions at the outplanting site that determines which morphological and physiological attributes of the seedling are important or even decisive for its survival (Riikonen & Luoranen, 2018; Kim M. Wilkinson & Douglas, 2014).

Nursing practices can have a decisive influence on the quality of seedlings. However, seedlings of different species may response differently to different nursing practices (Riikonen & Luoranen, 2018; Simpson & Ritchie, 1997). Nevertheless, there are some basic practices that positively influence the quality of seedlings. Since these practices usually involve more work and material, they are often associated with increased costs and thus seeds with a high quality may be very expensive (Kindt et al., 2005).

In addition to the desired quality of the seedlings, the quality of the seed also has an impact on nursery costs. The germination rate and thus the success of the work invested depends strongly on the quality of seeds , whereby the better the quality, the higher the germination rate (Tanaka, 1984).

Ensuring physiological quality and germplasm health

There are three main phases of crop development for seedlings: Establishment, rapid growth, and hardening (Kim M. Wilkinson & Douglas, 2014). Nursing practices from all three phases can be decisive for the later quality of the seedling.

In the first phase, the main aim is to germinate the seeds and for plants grown from cuttings to initiate the initial development of roots and shoots (Kuaraksa & Elliott, 2013; Kim M. Wilkinson & Douglas, 2014). At the very beginning, before sowing, impurities, such as damaged and contaminated seed, soil, or insects, need to be removed (Jaenicke, 1999). After that, care must be taken that the seeds are sowed at the proper density. The density has a significant and long-lasting effect on the seedling quality especially because it is decisive for the shoot-to-root. (Bonner & Karrfalt, 2008; Jaenicke, 1999). A good ratio in turn is important for a vigorous and healthy plant. At a high density, valuable space is saved, but the seedlings cannot form properly and are often stunted and are more susceptible to diseases (Bonner & Karrfalt, 2008). A too low density, on the other hand, may has negative implications on the shoot-to-root ration and, furthermore, wastes valuable space (Bonner & Karrfalt, 2008). However, different plant species have different needs and some species, for example smaller leaved and needle-leaved species, tolerate higher densities better than others (Thomas D Landis, Douglas, Wilkinson, & Luna, 2014).

Moreover, a growing medium of high quality and adapted to the needs of the species is fundamental for the health of the plant in general and in particular for the development of a healthy root system (Thomas D Landis et al., 2014). However, quality growing media or nursery soils are difficult to find and are often associated with high costs (Bonner & Karrfalt, 2008). Furthermore, the use of multinutrient fertilizer enhance the growth of plants during this phase. Moreover, the inoculation with mycorrhizal fungi or Rhizobium bacteria can support the growth of the plant and strengthen its resistance to disease (Jaenicke, 1999). Both measures involve additional work steps and thus additional work performance as well as additional material costs.

For plants grown from cuttings, this phase is also important for the initial development of the roots as they are not affected by diseases. Whereas the growth of the roots can be encouraged by treating the cuttings with rooting hormones, an infection can be prevented by disinfection of tools and appropriate storage, such as cooling (Kuaraksa & Elliott, 2013).

In the next phase, the objective is a rapid increase in size. To ensure an optimal growth and vigour of the plant, adequate quantities of fertiliser must be applied (Hardening & Landis, 2014). Furthermore, care must continue during this phase to ensure uniform growth and thus an optimal shoot-to-root ratio.

The last phase, the so-called hardening phase, aims to accustom the seedling to the conditions at the planting site in order to promote survival and growth following outplanting (Jacobs, Landis, & Wilkinson, 2014; Kim M. Wilkinson & Douglas, 2014). This phase is of critical importance because if the seedlings are not appropriately accustomed they may not endure the stresses caused by the outplanting and by harsh conditions at the planting site, such as drought or temperature extremes (Kim M. Wilkinson & Douglas, 2014). This can be associated with various actions that may entail a significant amount of work. Wilkinson & Douglas (2014) gives as an example the daily “brushing” of the seedlings to simulate the conditions of a windy planting site and with that improve the stem strength steadily before outplanting. Lastly, it is crucial to plant the seedlings at the right time. Jaenicke (1999) pointed out that if the seedlings are left too long in the nursery their quality may deteriorate considerably.

Table 17: Quality categories (low, medium, and high) and associated nursing practices with indicators. Only indicators are listed that have a major impact on the physiological quality and the health of the seedlings as well as on the costs.

	Physiological Quality and Health Requirements		
	Low quality	Medium quality	High quality
Nursing practices for seeds and cuttings	- Soil of unknown origin - No use of fertilizer or arbitrary application rate - No hardening	- Use of fertilizer but no site- and species-specific application rate - Hardening considers some conditions of the planting site	- High quality growing medium or nursery soil - Site- and species-specific application rate for fertilizer - Hardening considers all major conditions of the planting site
Nursing practices for seeds	- Very high plant density - No inoculation with mycorrhizal fungi and Rhizobium bacteria	- High plant density	- Appropriate plant density - High quality growing medium or nursery soil - Inoculation with mycorrhizal fungi and Rhizobium bacteria
Nursing practices for cuttings	- No encouragement of root growth with hormones - No measures to prevent infections		- Encouragement of root growth with hormones - Measures to prevent infections

Table 18 shows the effects of the three quality categories (low, medium, and high quality) on the cost components. for each tightening of requirements for the affected cost components we defined an equal linear cost increase of 25% of the costs that would be expected with only low-quality requirements.

Table 18: Effects of quality categories on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Storage**	
Physiological quality and health of seedlings	Low quality	-	1.00	-	1.00	-	1.00
	Medium quality	+	1.25	+	1.25	-	1.00
	High quality	+ +	1.50	+ +	1.50	-	1.00

While the costs of practices that aim to produce high quality seedlings are relatively explicit, the effects of high seed quality on the germination rate are far more difficult to quantify. While a higher germination rate generally reduces costs, and this is easy to demonstrate, the therefor required quality is difficult to quantify. However, since all authors agree that high quality, in addition to other conditions that must be met, has a favourable effect on the germination rate, for now, we are assuming a general reduction in labour and material costs of 20% when using high quality and 10% when using medium quality seeds (Table 19).

Table 19: Effects of the three quality categories on the cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Storage**	
Physiological quality and health of collected material (seeds)	Low quality	-	1.00	-	1.00	-	1.00
	Medium quality	-	0.90	-	0.90	-	1.00
	High quality	- -	0.80	- -	0.80	-	1.00

Ensuring genetic quality

Foremost, it is important to ensure that the sample assortment of seeds is labelled and that this labelling continues during all three phases of the development of nursery crops. Proper labelling ensures that the genetic composition of the collection is maintained and that genetic aspects, such as provenance, can be considered for outplanting.

Furthermore, with their practices, nurseries might be involved in genetic selection sometimes even without being aware of it (Luna, Wilkinson, & Dumroese, 2014). Luna et al. (2014) uses the speed of germination as an example. Due to economic considerations, nurseries may prefer fast-germinating plant individuals over slow-germinating individuals for reasons of efficiency. However, it could be that slow germination is an adaptive trait and therefore earliest sprouters may also be the healthiest and thus have a better chance of survival. With this practice, the nursery would have adversely reduced the gene pool and thus the genetic diversity of the population.

Table 20 summarizes nursing practices that are potentially decisive for the genetic quality of the seedlings.

Table 20: Quality categories (low, medium, and high) and associated indicators. Only indicators are listed that have a major impact on the physiological quality and the health of the seedlings as well as on the costs.

	Genetic Quality		
	Low quality	Medium quality	High quality
Nursing practices	- No labelling - Nursing practice select for specific traits	- inconsequent labelling	- Consistent labelling - No selection or selection when adaptive traits of the species are known

In Table 21, we have quantified the effects of the three quality categories (low, medium, and high) on the two cost components (labour and equipment). We see no or very marginal implications on the costs for equipment since no additional equipment is needed when genetic quality is considered in nursing practices. In regard to the cost component 'labour', on the other hand, we see a slight increase due to an increase in the amount of work involved, especially in connection with labelling. Furthermore, the efficiency of a nursery may slightly decease if traits that slow down the development process can no longer be selected out. All in all, however, we believe that the effects of considering genetic quality on cost are minimal. This is why we assume a linear cost increase of only 5% of the costs, which would be to be expected if genetic quality would not be considered at all in nursing practices.

Table 21: Effects of quality categories on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Storage**	
genetic quality	low quality	-	1.00	-	1.00	-	1.00
	medium quality	+	1.05	-	1.00	-	1.00
	high quality	+ +	1.10	-	1.00	-	1.00

Species diversity

The more species are germinated in a nursery, the higher its logistics costs are. The underlying assumption for this connection is that for each species a separate management plant might be necessary because the treatment should be tailored to the specific needs of a species. It is very difficult to quantify the additional costs caused by this. Not least because the additional cost per species depends on the type of treatment required by a species as well as the experience and management efficiency of the nursery. However, we expect a linear increase in costs per category of 15% of the costs that are expected if less than five species are propagated in a nursery (Table 22).

Table 22: Effects of species diversity on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Storage?**	
species diversity	< 5 species	-	1.00	-	1.00		
	5 – 15 species	+	1.15	+	1.15		
	> 15 species	+ +	1.30	+ +	1.30		

3.4 Cost of Outplanting and site preparation

As with the collection and nursing cost, the cost of outplanting are mainly qualitatively discussed in literature and in most cases in connection with guidelines and method descriptions. Some authors, however, provide qualitative information on the costs of outplanting associated with their field trials (Table 23). During the interpretation of this data we have again been confronted with the problem of different and/or unknown parameters. As far as possible, we have coordinated/adjusted them to each other.

The share of outplanting costs in the total costs of tree supply varies between ~20% and ~30%. A large part of this range is explained by influencing factors that can vary significantly depending on the nature of the associated system components. For example, different former land use practises on the planting site and with that different types of vegetation cover have a considerably different influence on the preparation costs (see also section 3.4.3).

Table 23: Outplanting and site preparation costs per hectare with a tree density of 1500 ha^{-1} in US\$. The table furthermore shows characteristics of the tree seed and seedling supply system which might have an impact on costs.

Former land use	**Cost components**	**manual/ mechan.**	**No. of species**	**Planting method**	**Country**	**Cost ha^{-1}** *Density*	**Author, Source**
pastures (2x) plantation (1x)	Labour[1] T&E[2] Transport	Manual	10	planting seedlings	Costa Rica	**\$303 – \$530**	(Zahawi & Holl, 2009)
N/A	Labour[1] T&E[2] Transport	Manual	6	planting seedlings	Thailand	**\$804** (wage adjusted)	(Kuaraksa & Elliott, 2013)
plantation sec. forest	Labour[4] T&E[4] Transport	Manual	5	direct seeding	Brazil	***\$38 - \$53***	(Cole et al., 2011)
plantation	Labour[1] T&E[2]	Manual	5	direct seeding	Brazil	**\$286[1]**	(Engel & Parrotta, 2001)
pasture	Labour[1] T&E[2]	Manual	5	direct seeding	Brazil	**\$438[1]**	(Engel & Parrotta, 2001)
N/A	Labour[1] T&E[2] Transport	Manual	6	direct seeding	Thailand	**\$565[5] (!)** (wage adjusted)	(Kuaraksa & Elliott, 2013)
pastures (2x) plantation (1x)	Labour[1, 3] T&E[2, 3] Transport	Manual	10	planting stakes	Costa Rica	**\$90 – \$158**	(Zahawi & Holl, 2009)
N/A	Labour[1] T&E[2] Transport	Manual	6	planting cuttings	Thailand	**\$804[5] (!)** (wage adjusted)	(Kuaraksa & Elliott, 2013)

[1] site preparation (roto-tilling, subsoiling, herbicide application, formicide application, irrigation, manual seeding)

[2] herbicides, formicide

[3] No fertiliser or insecticide application

[4] with fertilizer/insecticide application (calculation based on the costs for seedlings in the same paper)

[5] Includes post-planting maintenance

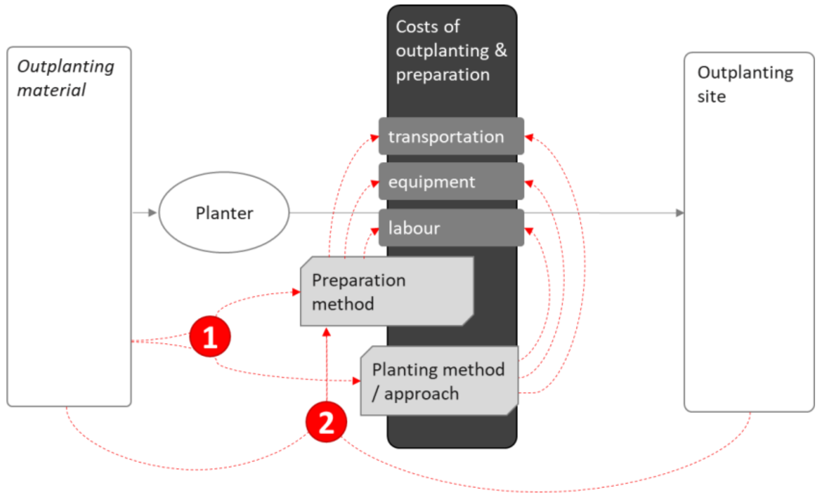

Figure 5: Components of the outplanting and site preparation costs with the most important influencing factors.

The costs incurred in outplanting and site preparation consist mainly of labour costs, equipment costs, and transportation costs. The amount of these cost components depends largely on the planting and preparation method, the choice of which in turn mainly depends on the characteristics of the planting site. The type of planting material has an effect on the choice of method by limiting it. For example, direct seedling is possible with seeds, but not with seedlings. In the following, we first discuss the share of each cost components in the total collection costs. We then describe how the outplanting material (No. 1 in Figure 5) affects the outplanting and preparation method. Finally, we discuss how the characteristics of the outplanting planting site affects the preparation method and with that the cost of outplanting (No. 2 in Figure 5).

3.4.1 Share of each cost components in the total costs of outplanting and site preparation

The authors Cole et al. (2011), Engel & Parrotta (2001), Kuaraksa & Elliott (2013) and Zahawi & Holl (2009) wrote down the costs related to the outplanting in a relatively detailed way, which allowed us to get a rough idea about the shares of the respective cost components in the total costs. The proportions shown in Table 24 are based on the average values of the data from the abovementioned articles and insights from the review of guidelines and methodological descriptions (see section 3.4.2 and 3.4.3). According to this data, the share of costs of equipment varies significantly between different types of planting stock. For example, the costs associated with planting stakes are much lower than that associated with planting seedlings or direct seeding (Zahawi & Holl, 2009). This is mainly due to the fact that stakes already have some competitive advantages over existing vegetation, such as their height, and thus less land preparation, e.g. application of herbicide, and maintenance, e.g. fertilizer, is needed. It is therefore expedient to consider the individual cost components dependently of the planting stock type. However, this example also shows that the costs are also related to the characteristics of the outplanting site. If there is no grass that could compete with sprouts, there is also no need to invest labour in removing it.

Table 24: Share of each cost components in total costs of outplanting and site preparation. A yellow colouring of a box indicates that the value in this box is an estimate and that it is mainly based on qualitative data and only partially on quantitative data. A red colouring indicates that the value in this box is only based on qualitative data. For values in boxes with a colour other than green, very little data was available for quantification.

Cost component	**Planting stock-raised in nursery from seed**	**Planting stock-raised in nursery from cuttings**	**Planting stakes**	**Direct seeding**
Labour	68%	68%	75%	74%
Equipment	30%	30%	5%	25%
Transportation	2%	2%	20%	1%

3.4.2 The impact of the type of outplanting material on outplanting costs

The type of outplanting material plays an important role in choosing appropriate methods and practices, and with that are decisive for the effort and equipment that is needed for outplanting. We first discuss how different type of outplanting material affect the site preparation before we discuss their effect on the choice of outplanting methods.

First of all, the outplanting material must be transported from the nursery to the planting site. As with the collection costs, it is the differences in the use of space that essentially make up the differences in transport. We therefore make the same assumptions as for the collection costs, with the transport of seeds causing the lowest costs and the transport of stakes causing the highest costs. The costs associated with transporting seedlings are somewhere in between. While Campos-Filho et al. (2013) states that a typical pick-up can transport about 12 times more seed than seedlings, Zahawi & Holl (2009) estimates a similar increase between seedlings and stakes. As with transport costs in connection with the collection of germplasm, these figures are merely orders of magnitude and may vary considerably depending on the size and shape of the seeds, the seedlings, and the stakes.

All type of planting stock need at least some land preparation prior to planting. The application of herbicide to suppress grass is one of them. In the field trial of Engel & Parrotta (2001), the application of the herbicide has caused costs of US$ 80 per hectare. Approximately one quarter of these costs are material costs and the rest labour costs. In addition to the use of herbicides or as a substitute to it, weeds can also be removed manually. This, however, is associated with a higher workload and thus with higher costs. The control of vegetative competition is beneficial for all type of planting stock. It has been shown that this measure has increased the survival of tree plantations in the tropics by up to 90% (Lowery, Lambeth, Endo, & Kane, 1993). However, different planting stock benefit to different degrees from weeding because they have different abilities to handle competition with other vegetation. For example, when planting seedlings, the existing vegetation has to be suppressed or removed in order to enable the seedlings to grow without competing for light. This is often not necessary with stakes. Stakes already tower over the existing vegetation at the time of planting, which frees them from the competition for light (Zahawi & Holl, 2009). This, however, does not apply for root competition for soil resources.

In addition to the competitive pressure from other plants, seedlings may also be hindered in their growth by herbivory. For some species, pesticides might be a way to deal with this. We assume that stakes again have an advantage over seedlings by having a greater resistant and accordingly little until no pesticide has to be used. Zahawi & Holl (2009), for example, did not apply any pesticide when planting stakes for their field trial.

In addition to the removal of weeds, seedlings of some species might also require rototilling (Engel & Parrotta, 2001). In addition, local conditions at the planting site may necessitate further physical soil treatments (see section 3.4.3).

Authors of all of the reviewed literature agree that direct seeding has the lowest outplanting cost (Cole et al., 2011; Engel & Parrotta, 2001; Kuaraksa & Elliott, 2013). A relatively large amount of seed can be sawn in a relatively short time with little effort and equipment. Kuaraksa & Elliott (2013), for example, sowed the seed directly on the soil along a line and then protected the seeds from wind and rain by placing sliced bamboo tubes on top of them. For planting seedlings, on the other hand, a planting hole is needed in order to ensure a good root-to-soil contact and with that to access water and mineral nutrients (Haase, Landis, & Dumroese, 2014). A variety of tools are available to dig the plant holes, from simple digging sticks to motorized augers (Haase et al., 2014).

Once the seedling is planted or the seed is sowed, further measures may be applied in order to support the establishment of the plant, such as fertilization, irrigation or artificial constructions for shading and shelter may. However, their necessity and efficiency depends essentially on the conditions at the outplanting site as well as on the needs of the plant species (Rose & Ketchum, 2002). In addition, the costs reported by the authors Kuaraksa & Elliott (2013) and Zahawi & Holl (2009) suggest that the type of planting stock may also be decisive for whether these additional measures are necessary and beneficial.

Table 25: A summary of aspects that may have an impact on costs. The figures show a rough qualitative weighting of the impact that a particular aspect may has on the respective cost component and how this differ between the type of planting stock. The colouring of the boxes is an indication for the robustness of the weighting. A green colouring indicates that the weighting is at least partially based on quantitative data. A yellow colouring indicates that the weighting is based on quantitative data. The weights in red boxes are assumptions. Corresponding data, which would support these assumptions, is lacking.

Cost Comp.	Drivers	**Direct seeding**		**Planting seedlings**		**Planting cuttings**		**Planting stakes**
Labour	Weeding (cutting or herbicide treatment)	+2	=	+2	=	+2	>	0
	land preparation (tilling)	+1	<	+1	=	+1	>	0
	planting	0	<	+1	=	+1	=	+1
	further measures (fertilization, protection from herbivory)	+1	<	+2	=	+2	>	+1
	Total	**4**	**<**	**6**	**=**	**6**	**>**	**2**
Equipment	Herbicides	+1	=	+2	=	+2	>	0
	Planting tools	0	<	+1	=	+1	=	+1
	Fertilizer, pesticides, etc.	+2	=	+2	=	+2	=	0
	Total	**3**	**<**	**5**	**=**	**5**	**=**	**1**
Transportation	Transportation	0	>	+2	=	+2	<	+3
	Total	**1**	**>**	**2**	**=**	**2**	**<**	**3**

Based on the defined shares of each cost component in total costs (Table 24), the above assumptions about the impact of the various cost drivers (Table 25), and costs reported by various authors (Table 23, section 3.4) we have broken down the total costs into the respective three cost components (Table 26). The figures in Table 26 represent only basic costs, which means that they do not include any additional cost drivers caused, for example, by the characteristics of the outplanting site. The effect of these cost drivers is discussed in the following sections. The total collection costs of each type of germplasm in Table 26 are therefore lower than the costs reported by the two authors (Table 23, section 3.4).

Table 26: Cost estimates (US$) for outplanting. Costs are per 1500 individual seedlings.

		Planting stock-raised in nursery from seed			Planting stock-raised in nursery from cuttings			Planting stakes			Direct seeding		
	Unit	ha-1	Costs	%	ha-1	Costs	%	ha-1	Costs	%	ha-1	**Costs**	%
Labour	$1.0 hr^{-1}$	280,0	280,00	68%	280,0	280,00	68%	98,0	98,00	75%	115,0	115,00	80%
Equipment	$1,0	125,0	125,00	30%	125,0	125,00	30%	8,0	8,00	6%	25,0	25,00	17%
Transportation	$1,0	7,0	7,00	2%	7,0	7,00	2%	25,0	25,00	19%	3,0	3,00	2%
Total costs			412	100%		412	100%		131	100%		143	100%

3.4.3 The impact of the planting site characteristics on outplanting costs

One of the main site characteristics that significantly influences outplanting costs is the type of the current predominant vegetation type (Cole et al., 2011; Shoo & Catterall, 2013; Zahawi & Holl, 2009). In most cases, this is related to the previous land use for agriculture or horticulture (cropping or grazing) or for plantations. According to Engel& Parrotta (2001), labour costs for preparing a site with grass as a predominant vegetation are approximately 1.8 times higher than labour costs associated with preparing a secondary forest or abandoned plantation for outplanting. This is mainly because additional measures might be necessary to physically suppress the dominant vegetation, for example by roto-tilling or burning prior to herbicide application (Engel & Parrotta, 2001). These additional necessary measures result not only in more labour costs, but also in additional material costs, for example due to a higher need for herbicides.

Table 27: Effects of the predominant vegetation at the outplanting site on cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**	
Vegetation at outplanting site	sporadic trees/shrubs	-	1.00	-	1.00
	dense trees/shrubs & grass	+	1.40	+	1.30
	grass	+ +	1.80	+ +	1.60

In addition to the characteristics of the ouplanting site itself, the characteristics of the surrounding areas may also influence the preparation costs. If, for example, free-ranging cattle graze in the surrounding areas or herbivorous wildlife is abundant in the surrounding forests, it may be necessary to either protect individual seedlings by netting or fencing or even fence the whole restoration area (Thomas D. Landis & Wilkinson, 2014). Although the effectiveness of fences is undisputed, they might also have a negative impact on the local fauna, for example by restricting the freedom of movement of wildlife.

Table 28: Herbivory pressure (low, medium, and high) and associated indicators. Only indicators are listed that have a major impact on the physiological quality and the health of the seedlings as well as on the costs.

	Herbivory pressure		
	High pressure	Medium pressure	low pressure
Livestock on neighbouring land	free range livestock on neighbouring land		No or fenced-in livestock
Wildlife density	low wildlife density	medium wildlife density	no wildlife or low wildlife density

We have defined the effects of herbivory (low, medium, and high pressure) on the two cost components (labour, equipment) in Table 29. For each tightening of requirements for the affected cost components (labour and equipment) we defined an equal linear cost increase of 10% of the costs that would be expected with only low-quality requirements.

Table 29: Effects of the herbivory pressure on the cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**	
Herbivory pressure	low	-	1.00	-	1.00
	middle	+	1.10	+	1.10
	high	+ +	1.20	+ +	1.20

Possible further cost drivers related to the outplanting site are the distance from the nursery as well as the access to the outplanting site, which might be impeded by difficult terrain or restricted accessibility for vehicles. To describe the reachability of the outplanting site we use the same indicators as for the reachability of the germplasm source (Table 5, section 3.2.3). Based on these indicators, we assume for each restriction of the reachability for both affected cost components (labour and transportation) an equal linear cost increase of 25% of the costs that would be expected if the reachability were easy (Table 30).

Table 30: Effects of the reachability of the outplanting site on the cost components labour and transportation.

		Labour		**Equipment**		**Transportation**	
Reachability of outplanting site	Easy reachable	-	1.00	-	1.00	-	1.00
	Aver. reachable	+	1.25	-	1.00	+	1.25
	Diff. reachable	+ +	1.50	-	1.00	+ +	1.50

3.5 Cost of post planting maintenance

The same authors who have already quantified the costs associated with outplanting have also explicitly mentioned the costs of post planting maintenance (Campos-Filho et al., 2013; Cole et al., 2011; Engel & Parrotta, 2001; Zahawi & Holl, 2009) (Table 31). In all projects, the duration of the post planting maintenance was 2 years. This is the time typically needed by seedlings to grow above the grass (Zahawi & Holl, 2009). The share of post planting maintenance in the total costs of tree supply varies between ~20% and ~32% for direct seeding and between ~35% and ~45% for planting seedlings. Of all cost pools, post planting maintenance thus accounts for the largest share of total costs.

Table 31: Post planting maintenance costs per hectare with a tree density of 1500 ha^{-1} in US$. The table furthermore shows characteristics of the tree seed and seedling supply system which might have an impact on costs.

Former land use	**Cost components**	**No. of species**	**Planting method**	**Country**	**Cost ha^{-1}** *Density*	**Author, Source**
pastures	N/A	5	planting seedlings	Brazil	**$1200 – $1800 (1-2Y)**	(Cole et al., 2011)
pastures (2x) plantation (1x))	Labour[1,2] T&E[1,2]	10	planting seedlings	Costa Rica	**$1200 – $1800 (1-2Y)**	(Zahawi & Holl, 2009)
pastures	Labour[1,2,4] T&E[1,2,4]		planting seedlings	Brazil	**~$1210 (1-2Y)**	(Campos-Filho et al., 2013)
plantation sec. forest	N/A	5	direct seeding	Brazil	**$15 – $30 (1-2Y)**	(Cole et al., 2011)
plantation	Labour[1,2] T&E[1,2]	5	direct seeding	Brazil	**$274[1]** **$155 (1y)** **$237 (2y)**	(Engel & Parrotta, 2001)
pastures	Labour[1] T&E[1]		direct seeding	Brazil	**~$400 (1-2Y)**	(Campos-Filho et al., 2013)
pastures	Labour[1,2] T&E[1,2]	5	direct seeding	Brazil	**$292[1]** **$137 (1y)** **$237 (2y)**	(Engel & Parrotta, 2001)
pastures	N/A	5	direct seeding	Brazil	**$90 – $180 (1-2Y)**	(Cole et al., 2011)
pastures (2x) plantation (1x)	N/A	10	planting stakes	Costa Rica	**$0 – $600 (1-2Y)**	(Zahawi & Holl, 2009)

[1]Weeding and/or herbicide (+application); [2]Formicide (+application); [3]Fertilizer; [4]Replanting

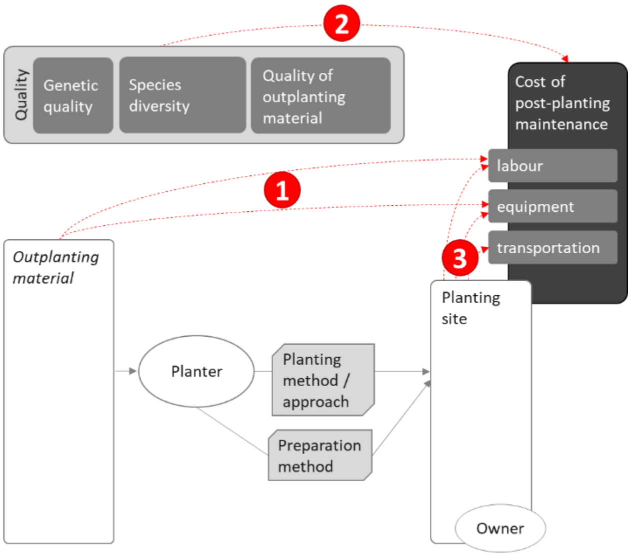

Figure 6: Components of the post-planting maintenance costs with the most important influencing factors.

The biggest threat to the development or the survival of planted seedlings and sprouts is competition from other plants and herbivory (Haase et al., 2014). In order to defy these threats, it is often necessary to continue actions that where already undertaken during outplanting. Accordingly, the two phases are very similar in respect of the resulting costs. Both cost pools mainly consist of labour and equipment costs which, in turn, are subject to the similar cost drivers. For example, the amount of work and material required for this phase also depends on how the land was used prior to the restoration and associated therewith the predominant vegetation before planting (No. 3 in Figure 6). We will only briefly discuss these relationships at the end of this section because they are in principle identical to those of the planting phase. Besides these similarities, the two cost pools do also differ. For example, much less labour and material expenses are to be expected in connection with planting activities. This is because fewer individuals have to be outplanted during post-planting maintenance since at this stage only the dead plants, or at least a proportion thereof, are typically replaced.

We start this section with a list of possible factors that can influence the mortality rate. These factors are directly related to the type (No. 1 in Figure 6) and the quality (No. 2 in Figure 6) of the outplanting material.

3.5.1 Share of each cost components in the total costs of outplanting

Only Engel & Parrotta (2001) recorded the costs related to post-planting maintenance in a detailed way which allows us to get an idea about how the post-planting maintenance costs are made up for direct seeding seedlings. For all other type of outplanting material, we lack this information. Furthermore, since Engel & Parrotta did not replace dead plants in their field trial, any costs that would arise in this regard are not included in their calculations. Therefore, and because similar measures are applied during post-planting maintenance and outplanting, we assume that the proportions of relevant cost components are very similar in both cases. Hence, with the exception of minimal adjustments for direct seedlings according to Engel & Parrotta (2001), the proportions in Table 32 are largely the same as for the cost pool outplanting (see section 3.4.1).

Table 32: Share of each cost components in total costs of post-planting maintenance. A yellow colouring of a box indicates that the value in this box is an estimate and that it is mainly based on qualitative data and only partially on quantitative data. A red colouring indicates that the value in this box is only based on qualitative data. For values in boxes with a colour other than green, very little data was available for quantification.

Cost component	**Post-planting maintenance for:**			
	planted seedlings	**planted cuttings**	**planted stakes**	**direct seeding seedlings**
Labour	67%	67%	70%	73%
Tools and equipment	30%	30%	10%	25%
Transportation	3%	3%	20%	2%

3.5.2 The impact of the type of outplanting material on post-planting maintenance costs

Different types of outplanting material and different species have different mortality rates and must therefore be replaced with different frequency in order to obtain the desired tree density. The mortality rate is influenced both by abiotic factors such as drought or extreme cold and by biotic factors such as herbivory (Nepstad, Uhl, Pereira, & Da Silva, 1996; Shoo & Catterall, 2013). While only limited measures are available to protect young trees in the post-planting period against adverse abiotic factors, such as individual shading or irrigation, the influence of adverse biotic factors can be partly prevented or at least reduced by appropriate measures. The extent to which such measures are necessary essentially depends on the competitiveness of the young plant. On the one hand, this is determined by the planting type itself and, on the other hand, it also depends strongly on the species. Although the competitiveness of a species may play an important role, we, for the sake of simplicity, cannot consider characteristics of individual species. We assume that the selection of species for a restoration project most likely reflects a large part of this range and thus includes those species that are rather highly competitive and those that are rather weak in competition. In the following, we will therefore focus on differences between type of planting stock.

As already described in section 3.4.2, stakes in particular are highly competitive due to their size at planting which reflects in a high survival rate. Zahawi & Holl (2009) reported in their study that most of the plants that have managed to establish themselves in the first year survived to the end of the study. Only some species continued to have a mortality rate beyond the first year. Accordingly, no or very little post-planting maintenance is necessary for stakes.

Seedlings need more care than stakes. Nevertheless, if they receive an appropriate amount of care, seedlings also generally have a relatively high survival rate, although this may also depend on the species (Cole et al., 2011). Cole et al. (2011) showed with their field trial that besides the species, the former land use on the outplanting site may also play an important role (see also section 3.4.3). While the majority of planted seedlings were able to establish themselves on former plantations, the authors found much greater differences in survival between different plant species planted on former pastures (Cole et al., 2011).

The highest mortality rate is to be expected with direct seeded seedlings. Only about 20% of all seeds mature into an established seedling (Grossnickle & Ivetić, 2017). Again, site conditions, predation and competition from other vegetation are suspected of being responsible for this poor performance (Grossnickle & Ivetić, 2017). In this regard, the slow growth of seedlings is a particular disadvantage of direct seeded seedlings and thus the longer duration until the competitive pressure from other vegetation, especially grass, decreases (Engel & Parrotta, 2001; Grossnickle & Ivetić, 2017). Accordingly, relatively extensive post-planting measures must be applied to increase the survival rate of these sprouts and maintain plantation stocking accordingly, which in turn is directly associated with high costs (Engel & Parrotta, 2001). Furthermore, the loss must be replaced by new plants. Although re-sowing seedlings causes only little labour and material costs, especially compared to planting seedlings, repeatedly replacing dead trees may significantly contribute to the total post-maintenance costs (Cole et al., 2011; Grossnickle & Ivetić, 2017). In the study of Kuaraksa (2013), direct seeding is only the most cost-effective option if a 100% survival rate is assumed. If, on the other hand, the costs are calculated per established plant, direct seeding is about 20 times more expensive than planting nursery raised seedlings (Kuaraksa & Elliott, 2013). Engel & Parrotta (2001) support this by concluding that the disadvantages resulting from a deep germination survival rate outweigh the advantages in many cases and that this is especially true with regard to costs. However, these costs do not relate exclusively to post-planting maintenance costs but reflect the total costs. Hence, the extent to which the increased mortality rate affects the overall costs of post-planting maintenance is not entirely clear. For example, Cole et al. (2011), on the other hand, concluded that costs for post-planting maintenance for direct seeded seedlings are approximately 10 times lower than for planted seedlings. Part of the difference in costs most possibly can be explained by site- or species-specific characteristics that are crucial for the mortality rate. But we are of the opinion that this cannot be the only reason to explain this significant difference. We therefore assume that the sowing strategies on which the calculations are based differ. For example, high costs suggest that all dead trees would always be replaced until the desired density is achieved. This, however, would only be necessary if at the beginning only the number of seeds was sown that corresponds to the desired tree population. Although this could be the case with very expensive and large seeds it is not a very likely scenario since a propagation in nursery would most probably be the preferred strategy in this situation. Low post-planting maintenance cost, on the other, hand might be a result if the mortality rate has already been anticipated by sowing a greater quantity and correspondingly fewer individuals would have to be replaced.

Table 33: A summary of aspects that might have an impact on post-planting maintenance costs. The figures show a rough qualitative weighting of the impact that a particular aspect may has on the respective cost component and how this differ between the type of planting stock. The colouring of the boxes is an indication for the robustness of the weighting. A green colouring indicates that the weighting is at least partially based on quantitative data. A yellow colouring indicates that the weighting is based on quantitative data. The weights in red boxes are assumptions. Corresponding data, which would support these assumptions, is lacking.

		Post-planting maintenance for						
Cost Comp.	Drivers	direct seed seedlings		planted seedlings		planted cuttings		planted stakes
Labour	Low competitiveness requires more maintenance: - weeding (cutting or herbicide treatment) - protection from herbivory	2	=	2	=	2	>	1
	More replacement due to high mortality rate (planting)	2	=	2	=	2	>	0
	Total	**4**	**<**	**4**	**=**	**4**	**>**	**1**
Equipment	Low competitiveness requires more maintenance: - herbicides, fertilizer, pesticides, etc.	2	=	1	=	1	>	0
	More replacement due to higher mortality - additional seeds and planting equipment	4		2		2		0
	Total	**6**	**>**	**3**	**=**	**3**	**=**	**0**
Transportation	Transportation	1	>	1	=	1	<	0
	Total	**1**	**>**	**1**	**=**	**1**	**<**	**0**

Based on the defined shares of each cost component in total costs (Table 32), the above assumptions about the impact of the various cost drivers (Table 33), and costs reported by various authors (Table 31, section 3.5) we have broken down the total costs into the respective four cost components (Table 34). However, except for one study, the costs in Table 31 do not include costs associated with replanting. Either because there were none or because plants have not been replaced. However, despite the uncertainties regarding costs associated with replanting, we considered them in our calculation by increasing the post-planting maintenance costs with a surcharge that varies between different types of outplanting material because of different mortality rates. For direct seeded seedlings we calculate a surcharge of 50%, for planted seedlings 20%, and for stakes 5% of the costs. Compared to the 20 times higher costs calculated by Kuaraksa et al. (2013), our surcharge is minimal. We cannot substantiate the amount of the surcharge with quantitative arguments, which is why we regard it as a placeholder until we have more precise data. For this reason, the values in Table 34 are subject to a great deal of uncertainty and therefore must be regarded accordingly with reservations. Furthermore, the figures in Table 34, represent only basic costs, which means that they do not include any additional cost drivers caused, for example, by the characteristics of the outplanting site or the quality of planting material. The effect of these cost drivers is discussed in the following sections.

Table 34: Cost estimates (US\$) for post-planting maintenance. Costs are per 1500 individual seedlings. Boxes in red indicate significant uncertainties (table above: not including costs for replanting; table below: including costs for replanting).

		Post-planting maintenance (not including costs for replanting) for											
		direct seeding			planted seedlings			planted cuttings			planted stakes		
	Unit	ha^{-1}	**Costs**	%	ha^{-1}	**Costs**	%	ha^{-1}	Costs	%	ha^{-1}	**Costs**	%
Labour	\$1.0 hr^{-1}	125,0	125,00	73%	680,0	680,00	67%	680,0	680,00	67%	210,0	210,00	70%
Equipment	\$1,0	42,0	42,00	25%	300,0	300,00	30%	300,0	300,00	30%	30,0	30,00	10%
Transportation	\$1,0	4,0	4,00	2%	30,0	30,00	3%	30,0	30,00	3%	60,0	60,00	20%
Total costs			**171**	**100%**		**1 010**	**100%**		**1 010**	**100%**		**\$300**	**100%**

		Post-planting maintenance (including costs for replanting) for											
		direct seeding			planted seedlings			planted cuttings			planted stakes		
	Unit	ha^{-1}	**Costs**	%	ha^{-1}	**Costs**	%	ha^{-1}	Costs	%	ha^{-1}	**Costs**	%
Labour	\$1.0 hr^{-1}	187,0	187,00	73%	812,0	812,00	67%	812,0	812,00	67%	221,0	221,00	70%
Equipment	\$1,0	64,0	64,00	25%	364,0	364,00	30%	364,0	364,00	30%	32,0	32,00	10%
Transportation	\$1,0	5,0	5,00	2%	36,0	36,00	3%	36,0	36,00	3%	63,0	63,00	20%
Total costs			256	100%		1 212	100%		1 212	100%		316	100%

3.5.3 The impact of outplanting site conditions on post planting maintenance costs

Whether and to what extent site conditions have an effect on the mortality rate depends on the species and on the type of planting stock (see section 3.5.2). Cole et al., (2011), for example, described that whereas some species in their study had a high mortality in pastures, they performed relatively well in plantations. Particularly responsible for these differences are factors that directly influence the competitive situation, such as poor light conditions cause by dense grass vegetation (see section 3.4.3). In addition to the above-ground competition, the authors also mention a possible below-ground competition as an explanatory variable, which is lower on former plantations because the cover grass and ruderal herbs have already been widely reduced (Cole et al., 2011).

Hence, to reduce the competitive pressure, substantially more post-planting maintenance is required in habitats with former grass cover. It can be assumed that due to the soil seed bank, even after the grass has already been largely pruned during the planting phase, further growth can be expected. In the study of Cole et al., (2011), the costs for post-planting maintenance on sites where seeds have been sowed directly on abandoned pasture were twice as high as for places that were previously used for plantations or are covered by secondary forest. Though not quite so big, Engel & Parrotta (2001) also reported in their study a difference between the different site conditions. In this study, the cost of maintaining trees which seed have been sowed directly on pasture land was around 15% more expensive than taking care for trees on former plantations (Engel & Parrotta, 2001).

The effects of the site condition on costs cannot be considered separately from planting stock types as their susceptibility to adverse conditions varies significantly between different types. However, because we have already included the different competitiveness with the mortality rate of the different planting types in the calculations in section 3.5.2, we assume for our calculations of the influence of different vegetation types an equal effect for all types (Table 35).

Table 35: Effects of the predominant vegetation at the outplanting site on the cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		Equipment	
Vegetation at outplanting site	sporadic trees/shrubs	-	1.00	-	1.00
	dense trees/shrubs & grass	+	1.45	+	1.10
	grass	+ +	1.90	+ +	1.20

As for the cost pool 'outplanting', possible further cost drivers related to post-planting maintenance is the access to the outplanting site, which might be impeded by difficult terrain or restricted accessibility for vehicles (see Table 5, section 3.2.3 for relevant indicators).

The accessibility indicators (distance from the road and terrain) mainly has an effect on the time necessary to apply respective maintenance measures, including replanting, and with that the labour costs. Based on these considerations, we assume for each restriction of the reachability for both cost components an equal linear cost increase of 25% of the costs that would be expected if the reachability were easy (Table 36).

Table 36: Effects of the reachability of the outplanting site on the cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		Equipment		Transportation	
Reachability of Outplanting site	Easy reachable	-	1.00	-	1.00	-	1.00
	Aver. reachable	+	1.25	-	1.00	+	1.25
	Diff. reachable	+ +	1.50	-	1.00	+ +	1.50

3.5.4 The impact of quality considerations on post-planting maintenance costs

Engel and Parrotta (2001) attribute a low initial survival rate and accordingly a high mortality rate among other things to suboptimal genetic and physiological quality of seeds. In particular, they mention maladaptation that was caused through a collection of seeds in locations where the conditions are different to the ones at the planting site (Engel & Parrotta, 2001). Although there is a broad consensus on the relationship between maladaptation and mortality rate (Loha et al., 2006; Rogers & Montalvo, 2004; Squillace & Silen, 1962), there are no studies or proven examples of how this would have affected post-planting maintenance costs or even led to the failure of the project (Rogers & Montalvo, 2004). Furthermore, Engels & Parrotta (2001) also attribute the high mortality rate of some seedlings to the poor physiological quality of the seeds, which may be related to a long storage period. This, however, mainly concerns recalcitrant seeds because they, unlike orthodox seeds, cannot be dried and stored because their viability decreases with the loss of moisture (Chris J. Kettle, Burslem, & Ghazoul, 2011).

Due to missing data, we had to make assumptions in order to quantitatively describe the relationship between quality and mortality rate (Table 37). The indicators in Table 37 are complementary to the indicators already developed for assessing quality in the collection and nursing phases. We want to underline the importance of both genetic and physiological quality for the success of restoration projects and the associated project costs. At this point, we also want to point out the need to further develop indicators to collect corresponding data in order to better understand the effects of physiological and genetic quality on tree seed and seedling supply system in general and its associated costs in particular.

Table 37: Quality categories (low, medium, and high) and associated indicators. Only indicators are listed that have a major impact on the physiological and genetic quality, and the health of the germplasm, as well as on the costs. Furthermore, the listed indicators are complementary to the indicators already developed for assessing quality in the collection and nursing phases.

	Physiological quality and health of planting stock		
	Low quality	Medium quality	High quality
storage (for recalcitrant seeds only)	- Long storage period (> 1 Year)	- Medium storage period (6-12 months)	- Short storage period (< 6 months)
	Genetic Quality		
	low genetic quality	medium genetic quality	high genetic quality
Provenance (risk of maladaptation)	- Is unknown - Conditions at collection site are very different from those at the planting site	- Is only partly known - Conditions at collection site are only partly comparable with those at the planting site	- Is known - Conditions are similar or identical with those at the planting site

In Table 38, we have defined the effects of the three (physiological and genetic) quality categories (low, medium, and high) on the three cost components (labour, equipment, and transportation). Different from the previously discussed cost pools, quality aspects do not cause costs during this phase but reduce them. We defined for each increase in genetic and physiological quality for both affected cost components (labour and transportation) an equal linear cost decrease of 15% of the costs, which would be to be expected if no or only very low quality were pursued.

Table 38: Effects of the three quality categories on the respective cost components. A red colouring of a box indicates that the value in this box is an estimate and that it is not or only partly based on quantitative data.

		Labour		**Equipment**		**Transportation**	
Physiological Quality and Plant Health	low quality	-	1.00	-	1.00	-	1.00
	medium quality	+	0.85	-	0.85	+	0.85
	high quality	+ +	0.70	-	0.70	+ +	0.70
Genetic quality	low quality	-	1.00	-	1.00	-	1.00
	medium quality	+	0.85	-	0.85	+	0.85
	high quality	+ +	0.70	-	0.70	+ +	0.70

3.6 Costs for campaigning

Genetic quality is often neglected during the planning or implementation of a restoration project (Bozzano et al., 2014; Dawson et al., 2014; Dedefo et al., 2017; Graudal & Lillesø, 2007; Roshetko et al., 2018; Thomas et al., 2014).. The reasons for this may be various but often it can be attributed to a lack of capacity on how to achieve and maintain quality and/or awareness about the importance of it (Riina Jalonen et al., 2014). In such situations an appropriate campaign may help to close this gap and thus create an important prerequisite for achieving sufficient quality in tree seed and seedling supply. Depending on the needs, the effort and thus the costs of campaigning activities may vary greatly. Due to the fact that only a few projects have taken genetic quality into account in their planning, we must assume that to date only a few such campaigns took place. Currently, we do not have any information on the extent of these costs.

For this reason, we are refraining from monetizing these costs for the time being.

→ Needs to be further elaborated

4. Discussion

The costs of tree seed and seedling supply are subject to various cost drivers (Figure 7). On the one hand, theses driving factors depend on the context and therefore cannot or only minimally be influenced by actors. On the other hand, cost drivers are directly influenced by decisions of actors.

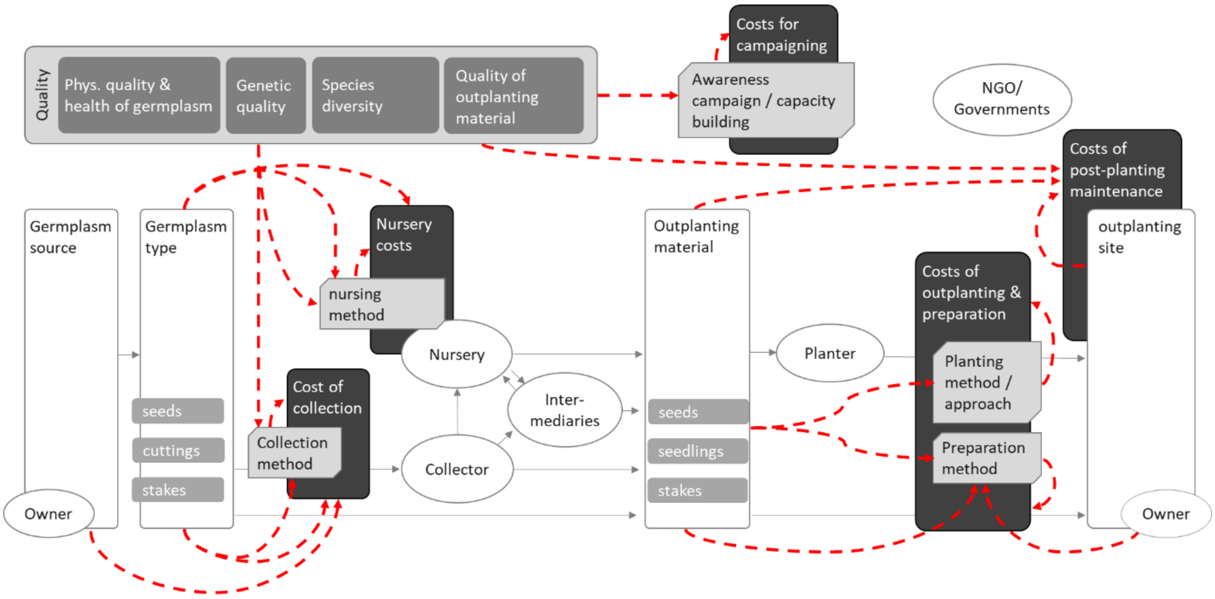

Figure 7: System image with the most important cost drivers (red dotted arrows)

The context-specific cost drivers include the characteristics and conditions of the area where the germplasm is collected and where the trees are finally planted. In particular, the characteristics of the outplanting site play a decisive role in terms of costs because it has an influence not only on the activities in connection with the outplanting and associated site preparation but also for the post-planting maintenance. Moreover, the activities during both phases are associated with high costs. Our cost model shows that the maintenance of the planted trees for a period of two years accounts for the largest percentage of total costs for all four planting methods (planting stock-raised in nursery from cutting and seed, planting stakes, and direct seeding). In the case of planting stock-raised in nursery from seed, for example, post-planting maintenance account for almost two thirds of the total costs. For direct seeding, the share of maintenance costs in total costs is with 45% slightly lower though still the largest cost component of the tree seed supply chain. The high proportion of post-planting maintenance costs results in a disproportional effect of all cost drivers that influence these costs compared to cost drivers affecting other cost pools with a smaller share. If we assume, for example, that the outplanting site is difficult to reach and, furthermore, is also covered with dense grass the maintenance costs for seedlings increase by around half. Thus, these two cost drivers (reachability and vegetation cover) also have a major influence on the total costs, which is demonstrated by the fact that around 40% of the overall costs are attributed to these two cost drivers alone. With a share of 36%, the cost drivers "vegetation cover" are particularly pronounced. Similar effects of the two cost drivers can also be seen in direct seeding. Only in case stakes are planted the vegetation cover has much less impact on costs (Table 39). This is mainly due to the fact that stakes already have some competitive advantages over existing vegetation and thus less land preparation and maintenance is needed.

Table 39: Impact of outplanting site related cost drivers (reachability of outplanting site and vegetation cover) on total costs. The table shows how much the respective costs increase if cost drivers are high (difficult to reach / grass as predominant vegetation type) compared to when they are low (easy reachability / trees/shrubs as predominant vegetation type). – For these calculations, all other cost drivers are low.

	Direct seeding	Planting seedlings (from seeds)	Planting seedlings (from cuttings)	Planting stakes
Share of post-planting maintenance in total costs when both cost drivers are low	low: 60% high: 61%	low: 64% high: 68%	low: 58% high: 63%	low: 49% high: 52%
Change in total establishment costs if both cost drivers change from 'low' 'high'	+82%	+70%	+62%	+12%
Share of cost driver 'vegetation cover' in total establishment costs if outplanting site is covered with grass	37%	34%	32%	0%
Share of cost driver 'reachability' in total establishment costs if outplanting site is difficult to reach	8%	7%	7%	11%

Similar to post-planting maintenance, the cost driver reachability and existing vegetation also have a significant impact on planting costs. However, the leverage effect on total costs is not as high, since planting costs are significantly lower. They account for between 19% and 34% of total costs, depending on the planting material and the characteristics of two cost drivers.

At the other end of the supply chain, the characteristics of the site where seeds are collected have a much smaller influence on the total costs. This is not surprising as the collection costs for seeds and cuttings are only between 1% to 6% of the total costs. When collecting stakes, however, the proportion is much higher (30%), which is mainly due to significant higher transport costs (Figure 8). Therefore, in the case of collecting stakes, the site characteristics have a much greater influence on the collection costs.

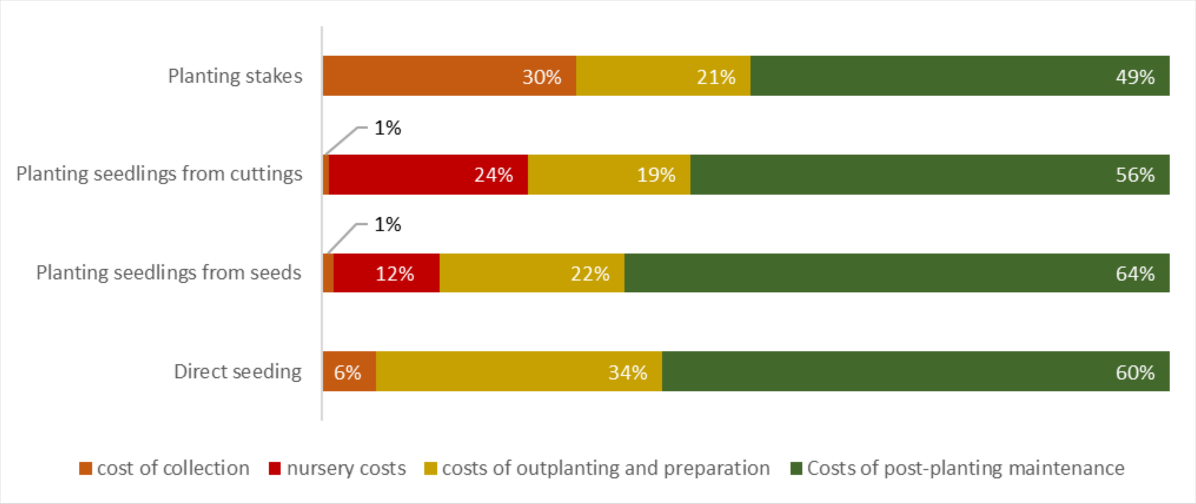

Figure 8: Share of different cost components in the total costs of tree seed and seedling supply per planting method. For this simulation, all cost drivers where low.

In addition to the context-specific cost drivers, the decisions of actors themselves might has a significant impact on costs. This applies mainly to decisions concerning the quality of germplasm, which in turn is reflected in the quality of planting material. For example, the collection costs increase by about one third if collectors aim for a high genetic diversity of seeds and thus collect seeds from several mother trees, compared to the costs incurred if seeds from only one or two mother trees are collected and the seeds thus have only a low genetic diversity. Although this is a significant increase in collection costs, the additional costs are negligible compared to the total costs. This is mainly due to the fact that collection costs only account for a very small proportion of total costs (fig 8). The impact of high diversity on total costs is only apparent after the seedlings or seeds have been planted on the planting site (Figure 9). Under the assumption that genetic characteristics are decisive for the adaptability of the seedlings to the site and thus increases the rate of establishment and with that increase survival, a suitable genetic constitution significantly reduces the costs associated with post-planting care. This in turn is directly reflected in lower costs. With the current assumptions made in this cost model, a high genetic quality would reduce post-planting maintenance costs by 30% compared to the costs that would incur with low quality seedlings. This in turn would result in a reduction of the total costs of approximately 18% (Figure 9).

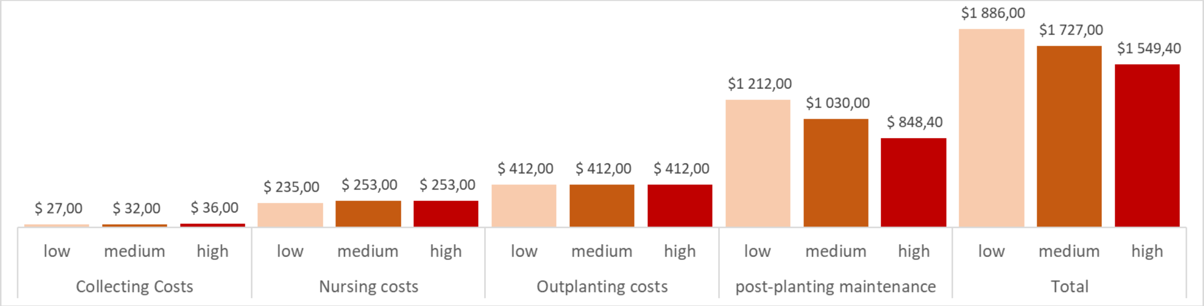

Figure 9: Effects of different categories of genetic quality (low, middle, high) on costs of planting stock raised in nursery from seed.

The effects would be even greater if, in addition to genetic quality, physiological quality aspects and species diversity were also taken into account (Figure 10). In this scenario, not only would the costs of collection increase significantly (+115%), but also the costs of nursing (+86%). However, despite these additional costs, the overall costs would be reduced substantially by 26%. This is mainly due to the fact that in this scenario considerable reductions in maintenance costs (-60%) are to be expected.

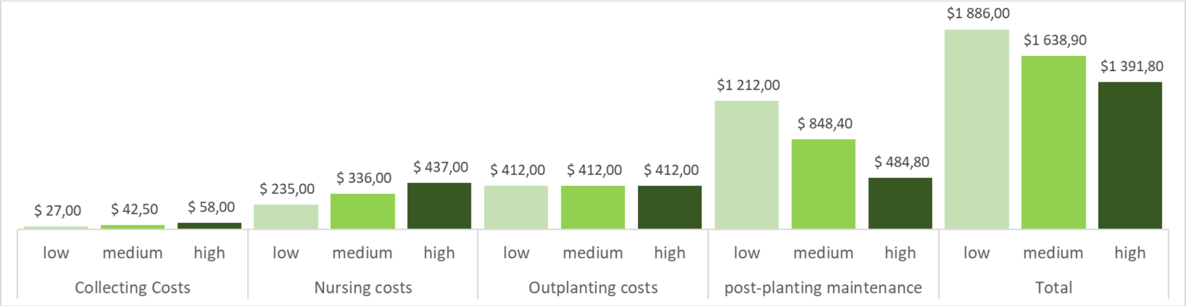

Figure 10: Effects of different categories (low, middle, high) of different quality aspects (genetic, physical) and of species diversity on costs of planting stock raised in nursery from seed.

Due to high variability of costs already within a restoration method, such as the planting of nursery-raised seedlings as described above, it is not surprising that authors who compare different methods come up with different results. For example, while Cole et al. (2011) showed that direct seeding costs only about 10% of the costs of planting nursery-raised seedlings, a review of studies conducted by Grossnickle & Ivetić (2017) found that this size ratio is, compared to other studies, rather big. Their review shows that the costs of direct seeding ranged from 9% to 51% of planting costs of nursery-raised seedlings and, in some cases, even exceeded them (Grossnickle & Ivetić, 2017). If we calculate the difference in cost between the two methods with the cost model presented in this report, direct seeding is about four times less expensive than planting nursery-raised seedlings and in the same order of magnitude as reported by Grossnickle & Ivetić (2017) (see Table 40 for comparison with other methods). Even if the underlying quality related cost drivers change, the size ratios between the methods are relatively stable as long as they are equally applied to all methods. However, there are clear differences between different site conditions, especially between planting stocks and other methods. This is because the costs associated with stakes are only marginally affected by the site conditions.

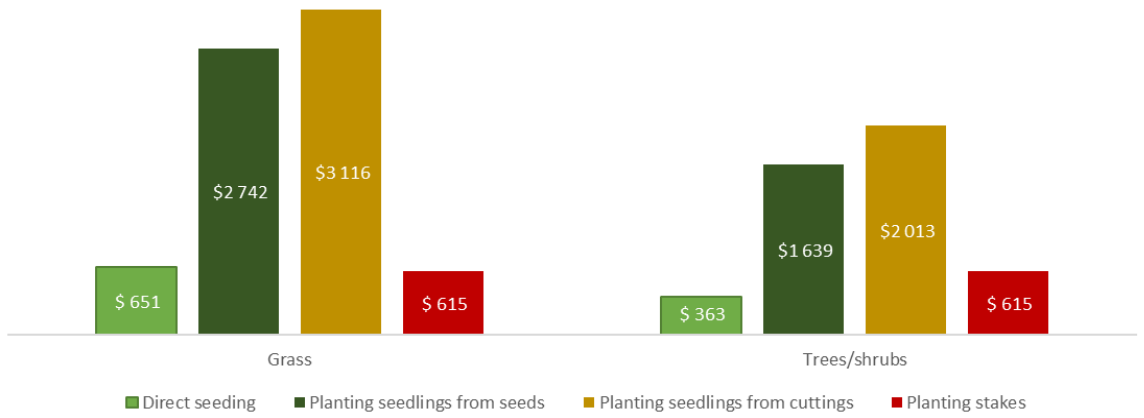

Figure 11: Cost of different restoration approaches for restoring land with either grass or trees and shrubs as predominant vegetation.

5. Conclusion

Statements about costs related to tree seed and seedling supply are often based on a qualitative argumentation. On only very few occasions have research projects or publicly accessible project reports recorded costs in detail and thus made them available to the public. It is thoroughly comprehensible why most authors are often arguing qualitatively. Characteristics of tree seed and seedling supply systems differ significantly between and even within regions, which in turn may translate directly into different cost structures (see chapter 3). While reviewing existing data, we have encountered a great variety of tree seed and seedling systems, and of approaches on how costs have been recorded. Comparing different projects therefore is very difficult and, in some cases, unfeasible. For example, although projects took place in similar geographical regions, they differed considerably in terms of their costs (Table 40). The reasons for this are manifold and, in some cases, not always clear. Costs were often only presented in an aggregated form and hence it was not always clear how these costs were composed and which parameters where included. A good example of this is the replacement of plants in the course of post-planting maintenance. Since this activity is potentially associated with significant costs, the consideration or omission of it may have a considerable effect on the total costs. The financial model presented in this report aims to explain these differences, as far as possible, by using variable cost drivers. To quantify these cost drivers, we compared, whenever possible, the average cost of an activity, e.g. cost of collection, from different projects with different constitutions and thus costs subjected to different cost drivers. This, however, was only possible for costs whose composition was comprehensible.

It is apparent that an accurate and standardized database would have helped us develop the cost model. Such a database would not only have allowed a more meaningful comparison of projects with fewer uncertainties, but also to better understand the underlying mechanisms, in particular the cost drivers. If we understand accurately how decisions, for example those regarding quality, affect the output of the tree seed and seedling supply and with that the associated costs and benefits, we can build a powerful model that helps to make better decisions. A model that serves as a framework that provides us with a holistic view of cause-effect relationships. We think this is important because, without this holistic understanding, decisions continue to be based on economic considerations that do not take the big picture into account. For example, strategies that place more weight on mass seed production and therefore prefer quantity over quality can only be economically feasible if the economic consideration ends with the delivery of the seeds or seedlings, but does not include the overall project objective, namely the establishment of a sustainable tree population. If that were so, quantity over quality would no longer be a desirable goal. By integrating and connecting different activities and decisions with costs and with that expanding cause-effect relationships over the entire supply chain, the model helps to counteract false incentives. If, for example, cost savings can be shown explicitly by using high-quality seed and seedlings and, furthermore, to what extent these savings can be traced back to decisions made in connection with collection and propagation, it would help to create the appropriate incentives, for example in the form of increased prices for seeds and seedlings.

Furthermore, we are also convinced that a meaningful cost model is an important prerequisite to better understand the benefits of restoration projects. Not only because costs are a firm component of a cost/benefit analysis, but also because a cost model provides a basis for a common understanding. Our cost model already presents some parts of the benefits, namely those that directly reduce costs along the tree seed and seedling supply chain. Our financial model ends after a two-year maintenance phase and considers but does not as yet integrate indirect costs (e.g. training costs, stakeholder consultation. etc.). Hence, we see the need to expand the model beyond this limit. Because costs will continue to be incurred but, above all, the greatest benefits of a project only become apparent in the long term. We propose the following steps for further action:

1. Validation of the framework. The main point here is to identify (1) whether the system presented in this report contains all the necessary components with regard to the cost model, (2) whether the dynamics within the system reflect reality. Furthermore, we would like to discuss (3) to what extent the system has to be adapted or extended in order to also depict potential benefits next to the costs .

2. Validation of the cost drivers. Many of the quantified impacts of cost drivers in this report are based on qualitative assumptions. The aim should be to replace these qualitative assumptions with concrete data in so far as possible.

Table 40: Overview of studies that explicitly mention the establishment costs in connection with their fieled experiment.

Type of germ-plasm	Planting approach	Reachability of collection site			Reachability of planting site			Vegetation cover at planting site			Quality of germplasm			Quality of planting material			Genetic diversity			Species diversity			Lab. known	Costs for collection (US$)	Costs for nursing	Costs for outplanting	Costs f.post-planting maintenanc	Total costs	Total costs according to cost model	Source
		E	A	D	E	A	D	G	T	T	L	M	H	L	M	H	L	M	H	L	M	H								
Seeds	Direct seeding		🟩		🟩					🟩		🟩					🟩				🟩		Yes	**15 – 45**		***38 - 53***	**15 – 30**	**68 - 128**		(Cole et al., 2011)
		?	?	?	?	?	?			🟩	?	?	?	?	?	?	?	?	?		🟩		Yes			**286**	**274**	**560**		(Engel & Parrotta, 2001)
																								15 – 45		**38 – 286**	**15 – 274**	**68-560**	**440**	TOTAL
		?	?	?	?	?	?	🟩			?	?	?	?	?	?	?	?	?		🟩		Yes			**438**	**292**	**730**		(Engel & Parrotta, 2001)
			🟩		?	?	?	🟩				🟩		?	?	?	?	?	?		🟩		Yes	**15 – 45**		***38 - 53***	**90 – 180**	**143 – 278**		(Cole et al., 2011)
		?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?		🟩		Yes			**565**		**565**		(Kuaraksa & Elliott, 2013)
		?	?	?	?	?	?	🟩			?	?	?	?	?	?	?	?	?	?	?	?	**No**	**353** (buy seeds)		**313**		**666**		(Campos-Filho et al., 2013)
																								15 – 45		**38 - 438**	**90 – 292**	**143 – 730**	**728**	TOTAL
	Planting seedlings	🟩				🟩		🟩				🟩		?	?	?	🟩				🟩		Yes	**23 - 30**	**225 – 375**	**303 - 525**	**1200 – 1800**	**1751 – 2735**		(Cole et al., 2011)
		🟩			🟩			!	!		?	?	?	?	?	?	?	?	?		🟩		Yes	**23 – 30**	**225 – 375**	**303 – 525**	**1200 – 1800**	**1751 – 2735**		(Zahawi & Holl, 2009)
		?	?	?	?	?	?	🟩			?	?	?	?	?	?	?	?	?			🟩	**No**	**1630** (buy seeds)		**2400** (3470 for 3Y)		**4032**		(Campos-Filho et al., 2013)
		🟩			?	?	?	?	?	?	?	?	?	?	?	?	?	?	?		🟩		Yes		**217**	**804**		**1021**		(Kuaraksa & Elliott, 2013)
		?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	No	**675** (aver. price/seedlings)		**4500**		**5175**		(Rodrigues et al., 2011)
																								23 – 30	**217-470**	**303-804**	**1200-1800**	**1021 - 5175**	**3150**	TOTAL
Cuttings	Planting cuttings	🟩			?	?	?	?	?	?	?	?	?	?	?	?	?	?	?		🟩		Yes		**552**	**804**		**1356**	**2480**	(Kuaraksa & Elliott, 2013)
Stakes	Planting stakes	🟩			?	?	?	!	!		?	?	?	?	?	?	?	?	?		🟩		Yes	**180 - 240**		**90-158**	**0 – 600**	**270 – 998**	**668**	(Zahawi & Holl, 2009)

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