SITE-SPECIFIC SILVICULTURE

Contents

Reclamation of Mining Lands

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Introduction

Worldwide, land has been significantly, and in some areas drastically, affected by mineral extraction. Societal pressures in most parts of the world now demand that after mining has ceased, someone (usually the mineral companies) should restore the affected land back to beneficial use, and this is controlled by legislation of various kinds and severity. Depending on a variety of factors including geology and landform, regional land use and ecology, climate and the views of community and landowner, the post-mining landscape may take a number of forms. Increasingly, the disturbance to the land caused by mining is used to advantage to regenerate the economic potential of the region or locality, increase the diversity of the landscape, and to enhance biodiversity and recreational value. In many parts of the world, trees, woodland, and forests are an essential part of this new landscape, following mining for materials that include lignite and coal, bauxite and other metal ores, aggregates, clays, and limestones.

The success of forestry schemes has not been assured – there has been considerable effort to improve reclamation standards by a growing understanding of the environmental and silvicultural issues involved. Even today, after several decades of modern research, forestry schemes can and do fail. This article will examine the main factors that must be considered in order to achieve the aims and objectives set for a woodland or forest planted on land previously used for mining.

Basic Principles

Trees have similar requirements on a post-mining site as they do in a forest: below ground, the provision of a nontoxic soil (or soillike) substrate to provide water, nutrients, air and anchorage, together with adequate climatic conditions above ground. The main issue for silviculturalists is that mined land often fails to meet these basic needs, so it is necessary for reclamation to take place according to their advocacy of the tree's requirements. Thus, the silviculturalist must have a reasonable understanding of basic biological tree needs, coupled with an appreciation of proper site and substrate characterization, and the ability to find a 'best fit' solution given inevitable constraints on substrate and site improvement. It can also be an advantage to think laterally in order to secure the best reclamation solution that will suit forestry planting. In addition to basic silvicultural concerns, forest establishment on often unstable and certainly fragile sites will require particular attention to the risk of soil erosion and surface water pollution. These needs usually require a team approach to land reclamation and tree establishment, and may include civil engineering and soil science in addition to silviculture. Other inputs may involve landscape architects and wildlife ecologists, as well as community consultation.

Reclamation of mined land is very dependent upon the manner of site preparation for mineral extraction, and subsequent site management (**Figure 1**). The most important factor determining the success of the forest re-established on the site is whether soil resources are identified, stripped, and stored sensitively. For sites to be mined, there should be no reason why soils are not stored for future re-use, but unfortunately many mined sites suffer from a paucity of soil or its damaged state through misuse. It is therefore vital that the silviculturalist gets involved in the process that will lead to forest establishment, preferably before any mineral has been extracted from the site.

Plans for the reclamation of the site should ideally be drawn up and agreed before mineral extraction. A soil resource survey and plans for final topography should enable an evaluation of the potential for the site. The actual plans for the site will be adjusted by the needs and wishes of the landowner, as modified

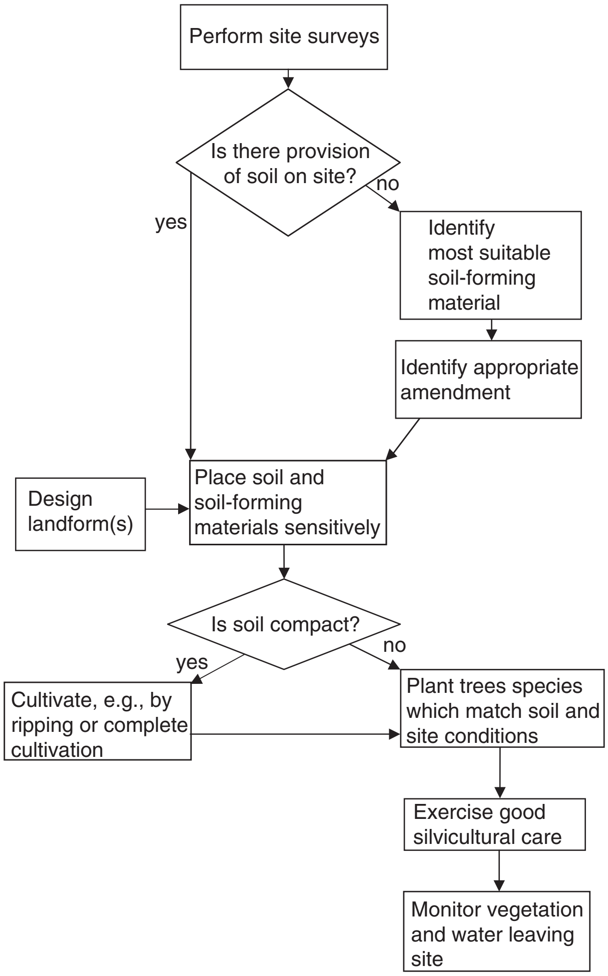

Figure 1 Basic stages of reclamation of mining land to forestry.

by community expectations, usually expressed through the planning process. In all these deliberations, it is important that the aims and objectives for any woodland established on the reclaimed site should marry with natural soil and ecological processes. In other words, the direction of reclamation and tree establishment should be similar to that which naturally occurs, or might be predicted to occur. In addition, it is desirable to trim expectations for the forest according to realistic assessment of the resources available to support it, and not to strive for forestry objectives, for example an expectation of high wood quality, that cannot be met without inordinate inputs of engineering, raw materials, and continual site maintenance.

Mineral extraction per se will pose a certain risk of environmental pollution, but technologies at the mining site for mineral concentration and processing and mineral waste disposal usually pose far greater risks which must be managed upon reclamation. Mineral tailings are a particular type of waste which results from mineral processing, and may form a significant area of the site, usually in lagoons of mineral material of small particle size (e.g., fine sand, silt, and clay). Depending on mineral industry, tailings can contain elevated concentrations of heavy metals or potentially toxic elements (PTEs) and are often very acidic due to the presence of pyrites (FeS_2). Such areas may require significant remediation (see below) if they are to support forest, though trees may be amongst the most suitable vegetation types as they are generally relatively tolerant of elevated metal concentrations. Furthermore, forests and woodland can act to phytostabilize these areas, significantly reducing both wind and water transport and redistribution of pollutants. Phytoremediation, the abstraction or destruction of pollutants, may also be a realistic goal in some cases, because tree metal uptake and rhizosphere activity can both help to decontaminate some sites. For example, some poplars and willows enjoy a reputation for metal uptake, and in intensive silvicultural systems such as short rotation coppice, site pollutant remediation may be possible in the long term. Nevertheless, decontamination will only occur within the depth of the root zone.

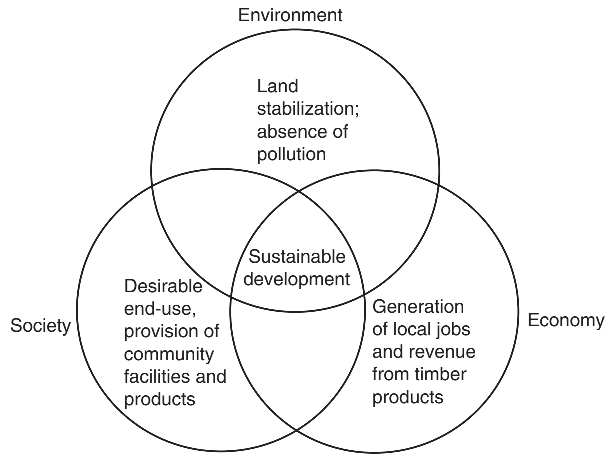

Figure 2 Mining reclamation to forestry and sustainable development.

An important principle is to plan a reclamation solution which is genuinely sustainable (**Figure 2**). From an environmental viewpoint, this is one that does not require repeated inputs of fertilizer, or continuing remedial attention to prevent water pollution. After trees are planted, it is difficult and cost-ineffective to right wrongs, and these should be scoped, predicted, and dealt with during the reclamation phase when earth-moving equipment is on site. From an economic point of view, the forest, if successful, should fully meet the aims set for it, and preferably generate income to support the silvicultural management inevitably required. Finally, the forest should meet societal aspirations and needs, whether for timber production, wildlife habitat, landscape stabilization or improvement, sport and recreation, or some or all of these. Forestry schemes that fail in some of these are likely to falter before they reach maturity. The management needs of the forest must be built into the plans for site reclamation, even though the responsibility for these may fall to agencies other than those responsible for the actual engineered reclamation solution.

Although satisfying the demands briefly described above may be a complex task, many examples worldwide indicate that successful woodland and forest reclamation can take place, testifying to the ability to avoid the weakest links in the reclamation chain.

Because mining technologies vary considerably according to geological circumstance and economic ability, there is a large range in the type of site and substrate presented for the silviculturalist to consider establishing forest on. It is therefore difficult to generalize effectively with broad reclamation guidance so that risk of failure is reduced adequately. It is essential that scientific (and other) literature relating to a particular mineral extraction and physiographic region is used effectively to build understanding of the local problems to be overcome. Nevertheless, there are some issues common to most mine sites which should be addressed, and these are discussed in broad terms below.

Landform and Drainage

The final landform of the mined site is usually partly determined by the nature of the geological obstacles to be overcome, and the original topography. Nevertheless, there are usually opportunities to input design into the final landform, and silvicultural needs should be included. For all sites, slope plays a part in affecting soil water drainage, and may be used to advantage in slowly permeable soil materials to reduce the likelihood of waterlogging. Slope angle, length, and form are also important in the control of soil erosion, and this should be dealt with by suitable engineering input. For relatively large sites where mechanical timber harvesting is in prospect, landform should be planned to facilitate this, and drainage located with due regard for the need for vehicular access. Roads should be designed at the same time as surface drainage, again by an appropriate engineering authority.

Surface water features are often sought on reclaimed sites. From an engineering viewpoint, these may serve as settling facilities to remove sediment before discharge of site waters into the main land drains and surface water system off-site. Suitably vegetated, e.g., with willows (*Salix* spp.) or reeds (*Phagmites* spp.), they may also help to remove water contaminants such as sulfates from the oxidation of pyrites. Water features can be attractive components of a reclaimed forest site, and will usually enrich its biodiversity and recreation potential.

Soil

Soil Selection

If soil materials are inadequate for forest establishment because of loss or degradation, there are two main options: (1) importation of substitute soil, or (2) soil manufacture using geological and/or waste materials. Option 1 is likely to be comparatively expensive if materials require purchasing, and there remains a need for strict quality control to prevent accidental importation of unsuitable (e.g., toxic) materials. For forestry schemes around the world, option 2 has been a mainstay in the absence of soil provision, and through considerable experience there is now strong guidance on this aspect of reclamation. There are usually good opportunities to select quarry wastes or reject materials, and possibilities to mix and blend to produce a desirable particle size range of soil-forming material. Reclamation of some mineral sites, e.g., after opencast coaling, will allow a wide choice of material due to the range of overburden materials, and it is important to characterize these fully with chemical and physical laboratory tests in order to select the most suitable for use. Here, the silviculturalist has a vital part to play by stipulating the kind of soil-forming material that will support the proposed forest. Sometimes, geological prospecting cores can be used to establish the range of possibilities before mineral extraction begins, but usually soil-forming materials will be identified during mineral extraction. It is important to have prepared guidance for machine operators so that they can select and store appropriate materials.

Some mineral substrates are intrinsically toxic and will not support satisfactory tree survival and growth without considerable treatment, for example some metalliferous mine tailings. If possible, such materials should be rejected as potential soil-forming materials in favor of less hostile materials rather than attempt to treat them. If there is little alternative but to attempt to establish vegetation, opportunities should be taken to cover these materials with whatever benign materials are available, even if these will not provide the full rooting depth of the trees and other vegetation types chosen. Of course, the underlying materials should be treated to minimize phytotoxicity before covering them, usually by controlling pH with lime or organic materials (see below).

Soil Placement

If original soil materials exist or can be saved before mineral extraction, reclamation can proceed routinely once final landform has been engineered. In hard rock quarries where a large void is created with steep sides, there will be limited opportunities for tree planting except in the bottom of the quarry. In soft rock quarries or opencast quarries where the product to overburden ratio is small, restoration to final landform involves the manipulation of overburden materials. Soils are then simply spread over them, provided slopes have been suitably engineered to allow this to take place and erosion risk has been assessed.

Soil (and soil-forming material) placement is at the center of good reclamation practice. Tree performance is severely hindered by soil compaction, which is often caused during reclamation by careless or misguided placement, or subsequent trafficking over newly laid soil. Compaction prevents deep rooting and therefore restricts the tree's ability to abstract moisture and nutrients. It can also cause surface waterlogging and ultimately lead to premature death or windthrow. Prevention is more certain than cure, and methods that spread soil without trafficking such as loose tipping are infinitely preferable to methods using earthscrapers or dozer tractors. The final configuration of the ground surface should be influenced by the climatic limitations of the site, and whether moisture retention against drought, or water shedding against waterlogging is the most important issue.

Soil Amendment

The principal difference between soil and soil-forming materials is the presence of soil organic matter in the former. This is the substrate which allows biological soil processes which in turn support and sustain plant life. In the absence of organic matter, soil-forming materials usually struggle to provide adequate nutrients to planted trees, especially nitrogen but also usually phosphorus. Soil materials put in storage often suffer from a loss of organic matter and a reduction in biological activity, but they generally recover if spread sensitively. In contrast, soil-forming materials may take decades or centuries to acquire organic matter levels comparable to those of normal soil. Research around the world has shown conclusively that it is extremely beneficial to amend soil-forming materials with organic matter at the time they are placed on the reclaimed land surface and awaits vegetation establishment. Materials such as sewage sludges or composted wastes are often used for this purpose, and **Table 1** gives more examples. Organic amendment can significantly improve the physical, hydrological, and nutritional qualities of the soil materials to be used. It may also reduce effects of acidity and metal toxicity, for example produced by the oxidation of pyrites. Soil placement methodologies using loose tipping can easily be developed to include the placement and incorporation of organic amendments, though for other technologies it may be necessary to consider premixing before the amended soil-forming material is finally placed on site.

Table 1 Examples of organic rich materials used as amendments in land reclamation to woodland

Raw sewage sludge
Digested sewage sludge
Thermally dried sewage sludge
Farmyard manure
Sugar mill waste
Paper mill sludge
Fish mort compost
Spent mushroom compost
Green (yard) waste compost
Municipal solid waste (MSW) compost
Wood residue

The size of organic material addition will depend on its chemistry, physical, and hydrological behavior, the evaluation of the amount required to produce a sustained supply of nutrients to the growing plantation, and the degree of risk posed to other receptors such as water bodies or humans who may visit the reclaimed site. It has been proposed that as a general rule, a reclaimed site requires between 1000 to 1500 kg N ha^{-1}, and this can usually be supplied by a manageable amount of organic material. It is desirable to achieve the addition of an amount that will supply tree nutrient needs until nutrient cycling via leaf fall and litter mineralization can provide the major source. A balance may have to be struck between this aim and managing the risk of water pollution from leaching and runoff. In some cases, it may be necessary to consider mixing more than one material, e.g., sewage sludge and papermill sludge, in order to achieve a more controlled nutrient supply.

Cultivation

It is still commonplace to require remedial cultivation in order to decompact soil (or soil-forming) materials prior to planting. This can be avoided completely if soils are loose tipped, but this may not be possible. Nevertheless, decompaction remains a vital operation – the comparative failure or poor performance of many tree planting schemes on land reclaimed after mineral extraction is due to lack of effort in achieving this. Techniques for decompaction will vary depending on available technology, ground conditions, and climate. In temperate countries, 'ripping' is commonly deployed, using a set of tines pulled by a crawler tractor. Fitted with 'wings,' these can be effective in loosening the ground, and ripping to depths of 1.5 m has been achieved in Australia, though depths of about 0.75 m are more common. Ripping is comparatively inexpensive, but it is prone to abuse by poor operator control, and loosened soil can recompact quite quickly. It must take place when the soil is dryer than the liquid limit to be effective in creating fissures and porosity. Ripping has been carried out both parallel and perpendicular to the contour.

Ripping is most suitable when a full soil sequence has been replaced on site because the operation generally keeps the soil horizons unmixed. It is not effective for mixing and incorporating organic amendments. Here, soil loosening with an excavator bucket also allows the incorporation process to take place with the same machinery, and 'complete cultivation' has proved very successful, if a little expensive.

It is obvious that, once decompacted, the ground so treated should not be trafficked by machinery if possible. Ripping can cause large stones to emerge at the soil surface, but stone picking and removal should only take place if such material will form a genuine impediment to tree planting.

Silvicultural Issues

Tree Stock and Planting

It is difficult to give useful generalizations because decisions about tree stock size, species, and density of planting will depend to a large extent on local environmental limitations and the particular objectives for the forest when mature. Experience in the UK has shown that it is important to be flexible in approach. There is a widespread belief that 'native' or 'indigenous' species are the most suitable for newly created sites such as those coming out of mineral reclamation, but this is challenged by considerable research. It seems sensible to choose species from those known to perform well on such substrates (including nonnatives), and to consider removing the least desirable species as thinnings when the forest matures, or to replant with more desirable species in a following rotation once the site has stabilized and nutrient cycling has commenced. Certainly, it is useful insurance to plant several species in group mixtures, so that some failures will not cause instability in the plantation as a whole. So-called pioneer species, such as willows (*Salix* spp.), poplars (*Populus* spp.), and alders (*Alnus* spp.) in the UK, tend to do well in the early stages of forest growth, and it is wise to use a significant proportion of these unless the site has been restored with original soil resources. These pioneers can tolerate the relative infertility that is usually associated with reclamation using soil-forming materials, and some are also able to withstand elevated concentrations of potentially toxic elements such as heavy metals.

Establishing forest blocks on post-mining land by application of tree seed is increasing in popularity. Seemingly ecologically more acceptable, especially if local seed sources are used, this technique has a place if carried out with due regard to seed dormancy (and seed is duly treated), and animal predation. The degree of silvicultural input is probably larger than with conventional planting, and the risk of failure is greater, but the results may look more naturalistic. Nevertheless, attention must still be given to the preparation of a suitable thickness of soil or soil-forming material during the engineering phase of reclamation.

Mycorrhizae and *Frankia* Inoculation

Initially, mineral sites restored using soil-forming materials can be almost microbiologically sterile unless organic amendments have been added. There has been considerable interest in the potential for purposefully introducing mycorrhizal fungi with tree stock in order to encourage survival and early performance on mined land. Several outlets now exist for the supply of material supposedly suitable for this purpose, but tree response is by no means assured, and local advice should be taken before embarking on a program of inoculation as a matter of course. In contrast, there is good evidence that when planting actinorhizal species such as *Acacia* spp., *Casuarina* spp., *Alnus* spp., *Elaeagnus* spp. or *Shepherdia* spp., only plants with Mycorrhizae and *Frankia* inoculation should be used.

Ground Vegetation

Although the importance of weed control is obvious, it is also the case that reclaimed post-mining sites often benefit from the establishment of a ground vegetation cover at the same time that trees are planted. For sites restored using soil-forming materials this vegetation will act immediately to facilitate the processes of soil formation which will benefit the site and the trees planted on it. While the trees are small, it will also 'green up' the site, improving its visual appearance and demonstrating commitment to the reclamation process. For sites restored using original topsoil, or amended with organic wastes, the correct choice of vegetation will permit effective control using selective herbicides – the alternative is to see a wide spectrum of weeds establish themselves that can be very difficult or expensive to control. For example, nonvigorous grass species are often chosen on reclamation sites in the UK, in order to hinder broadleaved weed germination while being susceptible to graminocide weedkillers. There has been considerable interest in the use of leguminous or actinorhizal plants as a significant component of a low ground cover, in order to provide or enrich the nitrogen capital of the site, and thus of the trees established on it. Choice will depend upon circumstance. However, it is important to ensure that such types of vegetation are truly infected with the requisite microorganism (usually confirmed visually by the presence of nodules on the plant roots).

Forestry objectives to increase biodiversity may demand that a ground flora of native plants be established, or vegetation similar to that which would be found under mature, seminatural woodland on neighboring undisturbed land. Nevertheless, these objectives should not obstruct the need to protect the tree seedlings from weed competition. In addition, the risk of fire should always be considered in the choice of ground vegetation cover.

Tree Protection

Tree protection is an important issue in all forest establishment, but imperative for forest planted on post-mining land. Unless reclamation operations have been exemplary, the site will still pose considerable problems for the newly planted tree, and silvicultural care must be first class. Weed control is usually vital but practice will depend on available technology and the size of the problem. Droughty sites, for example where stone content is high and organic matter content is low, should be given particular attention. So, too, should sites where organic amendment has taken place. Such materials usually promote rapid and large weed growth which can outcompete the planted trees for moisture, space, and light. Weed control may be necessary for several years on sites where tree growth is comparatively slow. Protection from animal browsing can also be important on reclaimed sites, and again, the form of protection will depend on the particular threat or threats. It may include fencing or individual tree protection; animal culling or control may also be necessary. Illegal grazing can be a significant problem in some parts of the world, requiring more severe measures if it is to be kept to tolerable levels.

Fertilizer Application

Infertility will require attention, and is commonplace when soil materials are not used for reclamation. Nevertheless, if organic amendments are used to improve both the physical and nutritional behavior of the soil-forming material, the use of mineral fertilizers may be unnecessary. And because funding for reclamation is usually more certain than that for maintenance, this approach is preferable to a reliance on one (or more) fertilizer applications during tree establishment. Fertilizers should be used with care, especially if soil materials contain little organic matter, because risk of leaching can be high. Fertilizer prescription should be based on soil or foliar analysis, or both. Local experience will guide interpretation, and, if limited, nursery or field experimentation may be warranted.

Site Monitoring and Maintenance

A forest established on sites reclaimed after mineral extraction is usually more susceptible to destructive agents such as drought, insect attack, or infertility than that on undisturbed land. It is therefore vital that attention be paid to the performance of the forest as it develops, especially in its early years. Regular site visits are necessary to check protective measures and the efficacy of operations such as weed control. Tree failure should be investigated and remedies put in place in case of significant loss. In addition, monitoring of water quality may be necessary for those sites where there is a risk of degradation of water quality, and consequent pollution to surface or groundwaters supplied from the site.

Conclusions

The principles of sustainability demand that land used for mineral extraction is brought back to beneficial use, and legislation around the world has been progressively tightened to ensure that this occurs. The largest responsibility for reclamation usually falls on the mineral operator. From an ecological viewpoint, a forestry after-use is often a serious candidate following mineral reclamation, though economic and social issues must also be taken into account. There is sufficient known about the science behind land reclamation to forest to suggest that high standards of reclamation practice are realistically attainable, and **Figure 3** shows examples of some successful schemes. Reclamation methodology is not overdemanding intellectually or economically. However, it is important for silvicultural issues to be put forward at the beginning of any

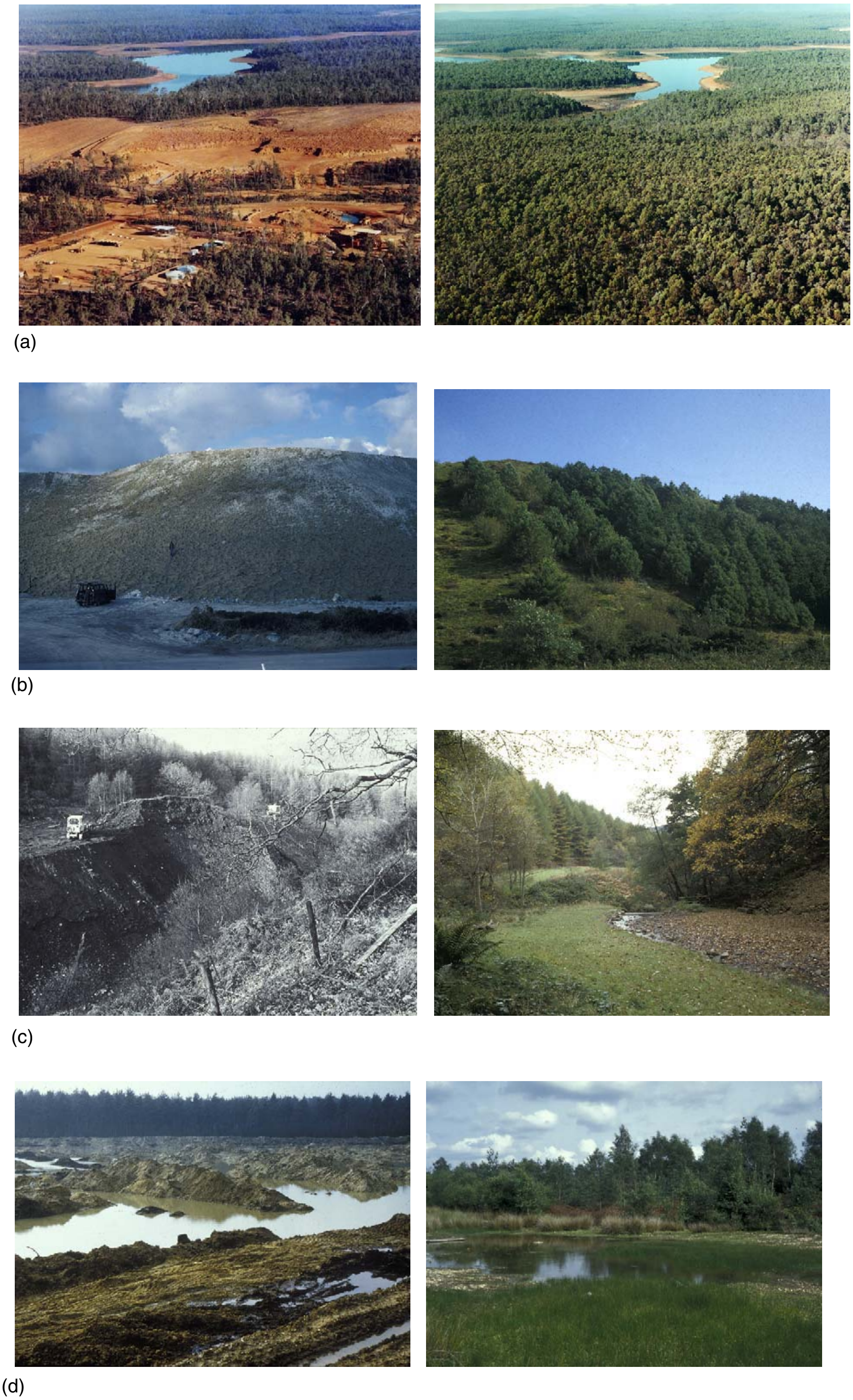

Figure 3 Examples of successful reclamation practice. (a) Bauxite mine in Australia during mineral extraction and about 15 years after reclamation (photographs by P. Garside). (b) China clay waste tip in Cornwall, UK before and 10 years after woodland establishment (photographs by A. Moffat). (c) Afan Argoed Country Park, Wales, UK during coal extraction and after reclamation (Forestry Commission). (d) Sand and gravel workings in southern UK before and after reclamation to woodland and wildlife habitat (photographs by A. Moffat).

reclamation project, understood, and then adhered to. There are many stages in the reclamation process, and failure at any of them will compromise forest performance. Effective management is therefore essential.

See also: **Afforestation**: Species Choice. **Landscape and Planning**: Forest Amenity Planning Approaches. **Site-Specific Silviculture**: Silviculture in Polluted Areas. **Social and Collaborative Forestry**: Social and Community Forestry. **Soil Development and Properties**: Nutrient Cycling. **Temperate Ecosystems**: Alders, Birches and Willows. **Tree Physiology**: A Whole Tree Perspective.

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Silviculture in Mountain Forests

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Mountain Forests are of Global Importance

What is a mountain forest? Definitions are, to a certain extent, arbitrary. Defining criteria usually include altitude, slope, and local elevation range (**Table 1**). Thus, steep mountain forests can also occur in the lowlands. Mountain regions cover 24% of the earth's land surface and contain 28% of the world's closed forests. Fifty-five percent of these mountain forests occur below altitudes of 1000 m above sea level. Mountain forests are found in areas with tropical, subtropical, temperate, and boreal climates. While only one in 10 people live in mountain regions, what happens in these regions affects many more people living in the lowlands. For example, deforestation in mountain forests may have an impact on climates and contribute to flooding in lower regions. Mountain forests are therefore globally important.

Rather than adopting a definition based on arbitrarily chosen ranges of altitude and slope, we take a silvicultural perspective in this article. Our focus is on those forests that require specific silvicultural treatments due to particular characteristics, or because they provide forest products and services associated with high altitudes and/or steep slopes. We therefore exclude, e.g., forests on flat highlands that are primarily used for timber production. We also exclude mountain forests in nature reserves since these are not silviculturally treated.

We first describe the characteristics of mountain forests, and then outline the silvicultural systems used in them. Since our areas of expertise focus on temperate mountain forests of the northern hemisphere, this article makes most reference to this forest type.

Mountain Forests are Different from Lowland Forests

Mountain forests of the montane and subalpine zones differ from lowland forests with regard to physical