from the grass layer for light, water and nutrients and the positive ripping effect is presumably a consequence of ripping de-compacting the soil, leading to greater water, air and root penetration.

A detailed cost-benefit analysis was undertaken to gain greater insight into the cost and value of each variable. This information will help develop realistic budgets for future restoration projects. For example, overall the most expensive components of the restoration were the collection and cleaning of seed (for both direct seeding and tube-stock propagation) and site earthworks. Scalping was the most time intensive and therefore costly of the earthworks, while ripping did not substantially increase costs. The cost of revegetation at a density of ≥ 3150 plants per ha ranged from c. $6,500 for seeded, not scalped and not ripped plots to approximately. $12,000 for planted & seeded plots that were ripped and ameliorated with lime and dolomite.

An experimental restoration plot for the threatened ecological community Lower Hunter Spotted Gum-Ironbark Forest approximately two years after revegetation. One of the more effective treatments that involved scalping and ripping can be seen on the right. Photo: Tricia Hogbin

Conclusion

We now have a good understanding of where to target restoration efforts; the methods needed to increase the likelihood of success; and the likely cost of implementing these methods. The next stage in the project is to facilitate implementation. The Hunter-Central Rivers Catchment Management Authority is already undertaking habitat protection and restoration within one of the identified landscape corridors. A multi-partner project, bringing together a range of stakeholders including state and local government, community and landholders is currently being developed to seek funding to implement habitat restoration and protection across the broader project area.

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Establishing native vegetation on the Mount Owen Mine model site

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The Hunter Valley

Together with agriculture, coal mining has substantially altered the landscape of the Hunter Valley in NSW. It is estimated that since European settlement, 76% of the vegetation communities in the Central Hunter Valley have been depleted and fragmented. This isolates local flora and fauna populations, leading to inbreeding, and potentially, population collapse. Creating corridors to re-connect vegetation remnants and augment them with restoration efforts is vital to their long-term survival and is an area in which mine rehabilitation efforts can play a significant role.

Development of the model site

A Model Site has been developed by the Centre for Sustainable Ecosystem Restoration (CSER) of the University of Newcastle at Mt Owen Mine with the support of Thiess P/L and Xstrata Coal. Mount Owen open-cut coal mine cleared 60% of the Ravensworth State Forest (RSF), a dry sclerophyll forest previously logged and grazed, leaving a large (northern) remnant and a small (southern) remnant. The spoil placement area for the mine is being progressively rehabilitated by forest or pasture topsoil being spread over the spoil with supplementary seeding or planting with tubestock. Offset areas which surround the mine are also being restored to woodland or forest ecosystems.

CSER research has extended into each of these areas with over 40 studies to date, and summaries of the research programs can be found on the CSER web site: www.newcastle.edu.au/research-centre/cser. Some key research insights are outlined below.

Pre-mining conditions

Most plants form symbiotic relationships with soil microbes (microscopic organisms, bacteria or fungi) which assist them in acquiring nutrients in exchange for carbon assimilated by the plant via photosynthesis. The soil bacteria rhizobia and *Frankia* fix nitrogen from the atmosphere, and supply it to wattles and peas or casuarinas. Endomycorrhizal fungi penetrate smaller soil pores, and ectomycorrhizal fungi can hydrolyse phosphorus from rocks and organic matter, thereby accessing nutrients not normally available to plant roots. However, many soils have a low capacity to form these root-microbe associations as a result of previous land use. Thus mine rehabilitation and offset restoration efforts are traditionally heavily reliant on the use of fertiliser. By re-establishing the root-microbe associations that provide sustainable nutrient acquisition, fertiliser use can be reduced.

The 'moonscape' of the Mount Owen spoil placement area and 8.5 years later. Photos: CSER.

Sampling has shown that organic carbon levels in Hunter Valley soils is low. Soil carbon is crucial for healthy, functional soils, as it supports soil microbial populations, increases water holding capacity and soil structure, and decreases soil dispersive properties. Increasing soil carbon will therefore make reconstructed systems more sustainable and resilient to environmental stresses such as drought.

Reconstructing functional soil - the importance of microbes

The spores of some soil microbes remain even in degraded ecosystems, such as in RSF, and when decompacted can have a high capacity for forming symbiotic associations with plant roots. However, if excessive fertiliser rates are applied to topsoil spread on spoil placement areas, the root-associations are unlikely to form and this can severely reduce the soil's potential for sustainable plant nutrition.

Mine spoil has very poor structure, but small spoil particles can be aggregated by plants and mycorrhizal fungi in the presence of an appropriate form of organic carbon, to form larger particles. This increases water, air and root penetration in the spoil. At least 3% organic carbon is required for this aggregation (Daynes *et al*., 2010).

Specificity between local plant species and rhizobia bacteria strains has been identified. Given the right combination, plants inoculated with rhizobia bacteria have been shown to grow better.

CSER has been developing a collection, and identifying, a range of native rhizobia from the Hunter Valley that can be cultured and reintroduced. Similarly, root cultures of mycorrhizal fungi are being maintained from a number of sites.

Topsoil transfer

Using topsoil from the target community (when available) is the best means of restoring a native vegetation community due to the seed bank and soil microbes it contributes. Some supplementary seeding may still be necessary to produce a full complement of vegetation strata. At Mount Owen Mine almost half of the native species found in the RSF have successfully grown on the spoil placement area primarily through the transfer of forest topsoil and associated seed bank.

Transferring forest topsoil to restoration lands is a cost-effective means of introducing native forest species, depending on the availability of sufficient quantities of forest topsoil, the size of the areas to be treated and the transport distance. Some evidence of dispersal from such sources into surrounding grassland has been found.

Amelioration methods

The following methods have been successful at Mount Owen Mine:

- Clay subsoil was found to be a good topsoil replacement. It increased native plant establishment, native species richness, plant growth and second-generation seedling establishment. Subsoils need to be characterised before use so as not to use dispersive material.
- Contour ripping the soil significantly increased plant survival and growth by decreasing soil compaction and therefore increasing water infiltration in both spoil placement areas and restoration lands. Ripping topsoil spread over spoil rehabilitation areas needs to be done soon after spreading to avoid losing plants that germinate from the seed bank. In areas where ripping is not possible, planting is best done in autumn when there is less water stress for plant establishment.
- While biosolids have been shown to have the capacity to boost native tree growth, the accompanying weed and grass growth out-competed native species when directly seeded.
- Municipal waste compost increased growth of Spotted Gum (*Corymbia maculata*) in spoil, with no negative impacts on photosynthesis. However, not all tested species responded equally well.
- Tree guards were particularly important for understorey and rainforest species survival and growth.

Weed control

Weed and grass propagules in some soils can produce excessive competition. In such instances it was better to seed directly on to spoil, plant tubestock or use a topsoil substitute, such as subsoil, rather than use weed-infested topsoil.

Weedy pasture topsoil can be capped with a weed-free material such as subsoil or reject material produced in the coal washing process (chitter) to suppress weeds and allow direct seeded native species to become established. In this scenario shallow, rather than deep ripping, scarifies the surface to reduce crusting and erosion, without re-exposing the underlying topsoil and stimulating the weed seed bank.

Scalping off the top 10 cm of topsoil in restoration lands was effective in removing the weeds and grasses and a large part of their seed bank, producing a higher native plant density from direct seeding than in un-scalped plots.

Experiment trialing the use of tree guards, fertilizer, watering and ripping in restoration lands at time of planting and 5 years later. Photos: CSER.

Seed dispersal and establishment of native plants into adjoining pasture areas was found to be poor in some areas. The seed bank was also dominated by exotic species. Active regeneration practices are therefore required to reconstruct native communities in these areas.

Acacia saligna has been shown to produce allelopathic chemicals that inhibit the growth of some native species. It is also promiscuous in its interactions with rhizobial symbionts, giving it an advantage wherever rhizobia are present. Cutting mature plants down and painting the cut stems with herbicide to prevent re-shooting has allowed good growth of planted canopy species that will eventually compete with *A. saligna* emerging from the seed bank.

Long-term research and monitoring

Long-term monitoring of spoil placement areas or restoration lands can provide evidence of resilience and long-term sustainability, e.g. following fire and drought. On-going research will contribute to the understanding of reconstructing ecosystems, allowing better outcomes to be achieved through adaptive management.

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