BIOGEOCHEMICAL CYCLES AND THEIR PRACTICAL IMPLICATIONS IN MANAGEMENT OF DEGRADED SITES BY RESTORATION FORESTRY

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BHOJVAID, P. P. 2003. Biogeochemical cycles and their practical implications in management of degraded sites by restoration forestry. One of the main objectives of "restoration forestry" is to suggest management options for improving degraded soil fertility through biological processes of trees. This aspect was formulated on the premise that the sustainable productivity of a natural ecosystem is derived to a great extent from the biogeochemical processes of litter and soil. These processes include biomass and nutrient accumulation by carbon assimilation, nutrient recycling by litter fall, root turnover and their subsequent decomposition and decay, resulting in humus synthesis. The soil fertility build-up and its sustainability is dependent not only on the maintenance of these activities at certain critical levels but even more importantly on their functioning as an integrated system with regulatory mechanisms operating in a synchronised manner. Essentially it means making acyclic processes more cyclic, thereby leading to improvement of structure and function of an ecosystem. However, little is known about the mechanism of these effects especially with respect to restoration of degraded sites by tree planting. The discussion in this paper is focused on these aspects of restoration forestry and their importance in field management of plantations based on biogeochemical cycles. It is envisaged that a judicious decision on management of a restored area would depend on such rotations that maintain and sustain the cyclic nature of ecosystems without jeopardising the production of such areas.

Key words: Ecosystem degradation - ecological rotation - restoration forestry - sustainability

BHOJVAID, P. P. 2003. Kitar biogeokimia dan kesan praktiknya dalam pengurusan tapak ternyah gred secara pemulihan hutan. Satu daripada objektif "pemulihan hutan" ialah mengesyorkan pilihan pengurusan untuk membaiki kesuburan tanih ternyah gred melalui proses biologi pokok. Aspek ini dirumuskan atas dasar bahawa produktiviti mapan ekosistem semula jadi terhasil terutamanya daripada proses biogeokimia sarap dan tanih. Proses ini termasuklah pengumpulan biojisim dan nutrien melalui asimilasi karbon, kitaran nutrien melalui jatuhan sarap, pusing ganti akar dan seterusnya penguraian serta pereputan yang menyebabkan sintesis humus. Pertambahan kesuburan tanih dan kemapanannya bergantung bukan sahaja pada penyenggaraan aktiviti ini pada aras-aras kritikal yang tertentu malah lebih utamanya ialah fungsi aktiviti ini sebagai sistem bersepadu yang dilengkapi mekanisme pengawalan yang beroperasi secara serentak. Secara asasnya, ini bermakna menjadikan proses asiklik lebih siklik agar dapat membaiki struktur dan fungsi ekosistem. Bagaimanapun, tidak banyak yang diketahui tentang mekanisme kesan ini terutamanya yang berkait dengan pemulihan tapak ternyah gred secara menanam pokok.

Perbincangan kertas kerja ini menjurus kepada aspek pemulihan hutan ini dan kepentingannya dalam pengurusan ladang berdasarkan kitar biogeokimia. Cadangan perundangan tentang pengurusan kawasan terpulih dijangka bergantung pada pusingan yang mengekalkan keadaan siklik ekosistem tanpa menggugat produktiviti kawasan tersebut.

Introduction

An overview of the global forestry sector suggests that forests can be classified into three major groups. While natural forests are being projected as reservoirs of biodiversity, and their conservation for ecological security of the world has been envisaged, major production of timber is realised from production forests, which occupy fertile lands. Such production forests are mainly plantations of superior genotype and are being raised as monocultures using intensive operations such as mechanised soil working, irrigation, chemical weed control and mechanical harvesting. The plantations of clonal *Eucalyptus* in Brazil, Radiata pines in New Zealand, hoop pines (*Arucaria* sp.) and its hybrids in Australia, and tropical pines in many tropical countries are some such examples (Evans 1992). The third main form of forestry is restoration forestry, which aims at ecological restoration of landmasses which have been degraded due to anthropogenic activities such as irrigation, application of fertiliser and pesticides, mining and natural calamities such as floods, erosions and drought (Singh 1982). Afforestation of deserts, alkaline and saline lands, waterlogged areas and mine spoils are some examples of this category of forestry.

The forestry scenario in India is no exception. Firstly, the National Forest Policy envisages that good natural forests are to be conserved for biodiversity, and as source of clean air and water as well as for conservation of soils. Secondly, the trees outside forests in various models of agroforestry, farm forestry and social forestry are contributing a major portion of pulp and small timber, particularly subsequent to the imposition of a moratorium on green felling (Anonymous 1999a). Finally, there have been efforts to restore large areas of degraded land in the country (Anonymous 1999b). Consequently, degraded lands such as alkaline saline lands, shifting and stabilised sand dunes, mine spoils, and waterlogged areas have been planted with tree species throughout the country under various programmes of Wasteland Development Board and Eco-development Board in the recent past.

One characteristic feature of restoration forestry in India and in other developing countries is that such restored sites are clear felled and brought under alternate land use systems such as agriculture and pastures to meet the demands of grains and fodder for teeming populations of these nations. Furthermore, the tree species planted for reclamation are invariably fast growing tree species such as *Eucalyptus, Poplar, Prosopis* and *Ailanthus.* These species not only restore degraded lands, but also produce fuelwood, pulp and small timber for local populations. I intend to demonstrate in this paper that production forestry from already degraded and derelict soils by use of quick growing tree species is not an ecologically sound practice. The main objective of planting trees is to establish a closed soil-plant-nutrient cycle, which needs to be maintained in order to achieve restoration of physical, chemical and biological properties of soils. Furthermore, application of special management practices based on ecological rotation to such reclaimed lands can lead to production of wood on sustained basis.

This paper is organised into two sections. The first discusses degradation of soils following deforestation and excavation for mineral ores or other degradative forces such as irrigation induced secondary salinisation. This section also examines the dynamics of major plant-soil processes following biological restoration and tree planting in the context of four succession stages that operate in the degradation and restoration of sodic soils. In the second section I will introduce a conceptual model for the sustainable management of plantations established on degraded sites based on information in the literature and results from my previous study (Bhojvaid *et al.* 1996, Bhojvaid 1998, Bhojvaid & Timmer 1998).

Degradation-restoration cycle

Degradation phase

Ecosystem degradation occurs as a result of natural or anthropogenic environmental change that alters the patterns of productivity, nutrient cycling and size distribution in biota (Singh 1982, Bradshaw 1983). Degradation, however, can assume different intensities and may result in partial or complete destruction of vegetation or loss of soil horizon, soil structure and soil fertility. In essence, vegetation loss may be accompanied by total loss of soil, in either a biological or a pedological sense.

In mined areas, excavations for mineral ores result in removal of vegetation cover and in induction of toxic conditions, which may range from adverse soil reaction and salt imbalance to accumulation of heavy metals. Organic matter is lost due to its fast decomposition as a result of altered microclimate. Furthermore, aggregate breakdown and slaking of soils are very common due to the use of heavy machinery for mining. These factors may operate simultaneously to adversely affect soil structure and aggregate stability leading to adverse soil infiltration and hydraulic conductivity (Quirk 1986, Chhabra 1996). Thus, the degradation sequence operates in an open system that is highly prone to erosion and surface run-off, which may further aggravate the degradation processes.

Establishment phase

During plantation establishment, special root-zone management techniques may provide an enhanced belowground microclimate for plant establishment and early growth. Plant survival is enhanced by the addition of site-specific amendments. The incorporation of VAM and/or farmyard manure may provide nutrients for root extension and juvenile tree growth. Tree growth and associated crown expansion result in the onset of canopy closure by five to 10 years. Thus, the establishment phase is characterised by an enhanced accumulation of biomass and nutrients in trees and relatively small changes or improvements in soil properties. Eventually, ecosystem development in terms of structure (nutrient accumulation and biomass assimilation) is driven primarily by vegetation growth. This contributes to initial chemical reclamation of the site, which is characterised by reduction in toxicity and improvement of ionic balances at exchange complexes.

Transition phase

Crown closure results in moderation of microclimate under the tree canopy and facilitates the initiation of biological activity in the degraded sites being reclaimed. This leads to significant build-up of microbial population and extension of the root system. The biological activity of roots and microorganisms increases CO_2 production in the soils. This mobilises insoluble $Ca(CO_3)$ and facilitates replacement of toxic ions by calcium ions on the ion exchange complex of the soil. Vertical and lateral expansions of root system lead to the formation of channels in the soil profile. This facilitates water infiltration and water movement in the soil leading to higher moisture holding capacity.

Therefore, subsequent to onset of crown closure, ecosystem restoration is driven more by soil and plant biological processes than by tree establishment. Soil fertility indicators, such as soil organic matter content, N status and concentration of major nutrients are elevated via the build-up of organic matter, litter production and root turnover in the transition phase. The litter provides substrates for nutrient cycling and the decomposition of litter enhances soil-nutrient status. However, the structural composition (species richness) and functional diversity (biomass and nutrient distributions) of the plantation system as a whole indicate that the ecosystem is still "leaky" in terms of nutrient cycling (Figure 1).

Fallow enrichment phase

With increasing age, the trees return more biomass to the forest floor and soil as litter and root decay respectively. This is typically characteristic of the fallow enrichment phase (15–30 years), a phase of fertility building. Although soil toxicity may further decline during this phase of the restoration cycle, relative change is not as pronounced when organic matter content, N status and macronutrients are considered. Moreover, the structural composition (species diversity) and functional diversity of the plantation system increases significantly, reflecting the operation of a "tighter nutrient" cycling system. This contributes to the restoration of soil fertility (Figure 2).

Conceptual model for sustainable management

Soil organic matter content is a major indicator of sustainable landuse because of its key role in maintaining the structural, hydrological, biological and chemical properties of soils that increase soil fertility and productivity (Prinsely & Swift 1986).

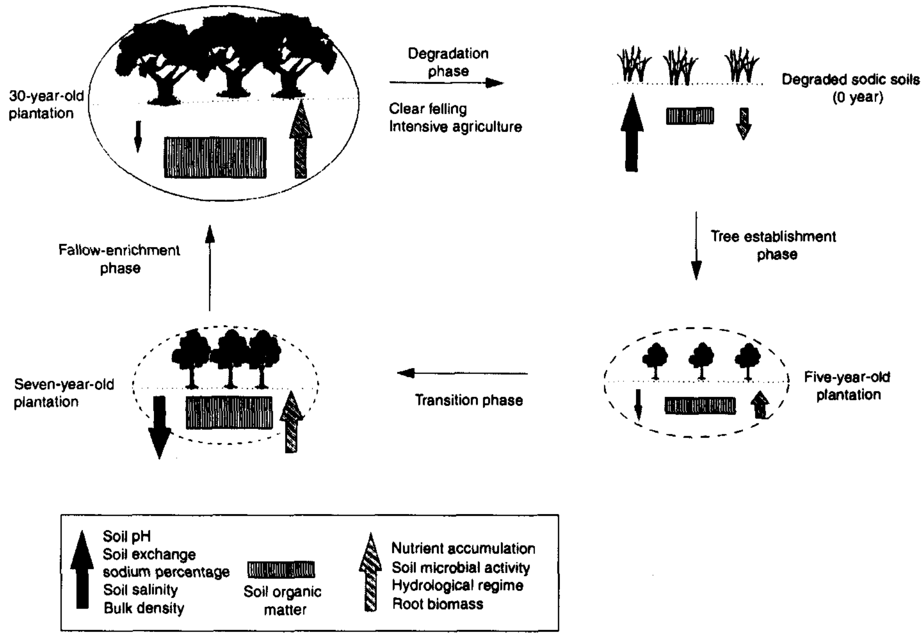

Figure 1 A conceptual model of the restoration of sodic soils by *Prosopis juliflora* plantations in a 30-year cycle leading to sustainability of ecosystem. Size of rectangle represents the build-up of soil organic matter. The degree of "closeness" and "leakiness" of system is represented by solid and broken ovals respectively.

A management system that allows the maintenance and/or enhancement of soil organic matter for present generations without compromising future productivity, therefore, should qualify as a sustainable system (Young 1986).

Sodic soils differ in character and behaviour from normal soils of the humid tropics and those of temperate climates. Sodic soils commonly have lower accumulation of organic matter because it is broken down more rapidly. Thus, sustainability in the context of this paper is defined as the maintenance and/or enhancement of organic matter build-up in the soils (Young 1989). This is mainly driven by carbon assimilation and photosynthesis in living biomass and its movement to the soil via litterfall and root turnover (Fisher 1995).

Conceptually, soil fertility is a function of soil organic matter content, total N content and available phosphorus and potassium. Typical agricultural crops, such as wheat, respond to the application of N, P and K with enhanced uptake of these elements relative to Ca and Mg (Swarup 1994). The results in many earlier studies show that the ameliorating effect of trees in terms of crop nutrition is driven to a larger extent by removal of toxic elements and subsequent replacement of Ca and Mg ions in the soil exchange complex in initial years of restoration process. The parallel process of building up N, P and K supplies in the topsoil by litter fall, organic matter accumulation and root turnover becomes significant only in later stages of plantation development (Bhojvaid *et al.* 1996, Bhojvaid 1998, Bhojvaid & Timmer 1998).

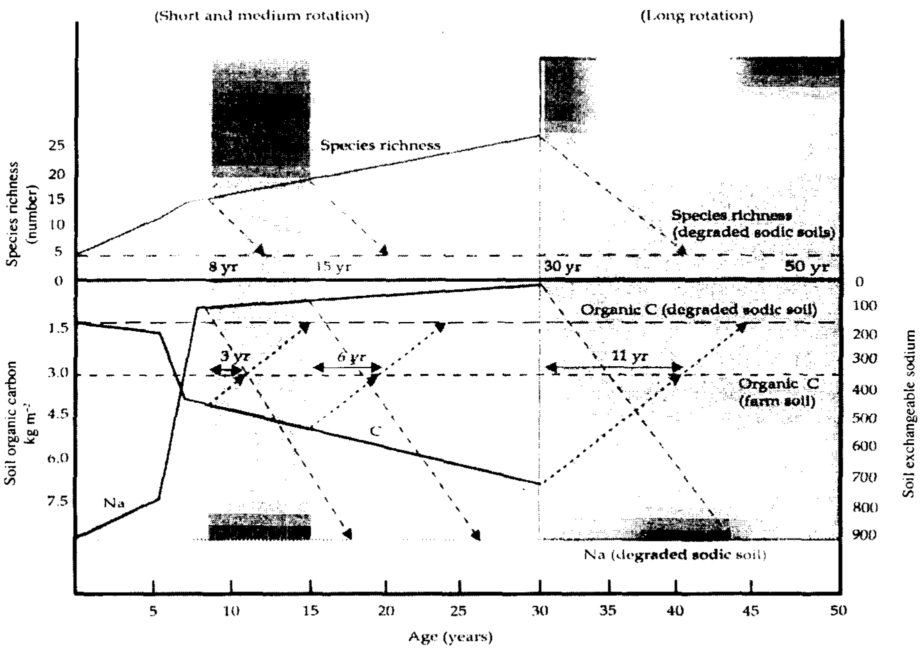

Figure 2 A schematic representation of changes in soil organic matter, exchangeable Na and species richness in *Prosopis chronosequence* under short-, medium- and long-term rotations following clear felling and intensive crop production. The solid lines represent build-up of soil organic matter, species richness and reductions in Na toxicity following reforestation of sodic soils. Probable degradation rates of these parameters after clear felling and conversion to agricultural production are shown by dashed lines with arrows. The shaded areas represent short, medium and long rotation lengths.

Processes to increase fertility becomes more important in the fallow enrichment phase after soil toxicity is reduced to a non-toxic level in the transition phase. Thereafter, restoration is driven primarily by the accumulation of organic matter and its effect on physical and chemical properties of soils. The structural diversity (species richness) of the plantation system increases considerably during the fallow enrichment phase. Presumably, the prolific root system of understorey vegetation and trees at the soil surface facilitates the absorption of nutrients released from decaying vegetation biomass and limit nutrient loss from the system. This makes nutrient cycling more efficient and "tighter". Therefore, the older plantation system (> 30 years) is functionally mature as reflected by higher organic matter and higher nutrient accumulation in the soil and vegetation compartments. Moreover, the older plantations have a higher structural (species) diversity in the understorey vegetation and soil macrofauna (Figures 1 and 2).

Kimmins (1986) proposed that three critical factors tend to control the sustainability of forests in the face of natural and human-induced disturbances. These are the extent of damage to structure and function of an ecosystem, the potential rate of recovery of an ecosystem following disturbance, and the duration between two subsequent disturbances. A tree rotation, which allows the site to return to the ecological conditions that existed prior to tree felling is called an ecological rotation and its length is governed by nutrient capital of the site (Kimmins 1977, 1986). Thus, if long-term maintenance of soil fertility and site nutrient status are the objectives of management, tree rotations should not be shorter than nutrient recovery rotations.

The aspect of soil sustainability under various rotation lengths is shown schematically in Figure 2. Assuming that degradation occurs at constant rates, it is clear that high reserves of soil organic matter will prolong organic matter depletion by 11, six and three years in long, medium and short rotation management respectively. Similarly, loss in species diversity will also be delayed with longer rotations. Of course, continuous forest production by harvesting and replanting would maintain or increase soil fertility, thus contributing to shorter future rotations.

The results of soil dynamics and stand development from earlier studies that identify three distinct phases along the restoration continuum of plantation development over a 30- to 50-year period also provide insight into the aspects of the sustainability of plantations following harvest (Fisher 1995). Although a short restoration period of seven to 10 years may rehabilitate the productivity of sodic and other degraded sites to the level observed in normal farm soils, the site nutrient capital and system reserves of the site may still not be sufficient to support optimum tree growth in the next rotation. Thus, site nutrient depletion by crop harvest may exceed observed rates of nutrient build-up in the reclaimed mined sites. This would result in loss of productivity in successive rotations (Young 1989). Clear felling would also result in the removal of plant cover. This will change the understorey climate and associated restoration processes (Fisher 1995). Thus, short rotation years may not be ecologically suitable to maintain sustained production on reclaimed mined soils. In contrast, a selective thinning operation would maintain the microclimate and facilitate the continuation of processes involved in fertility build-up and toxicity removal. System nutrient reserves and improvement in soil structure and the hydrologic regime of mined soils, as reflected in physical and chemical soil properties under the canopy of 30- to 50-year-old stands, suggest that a longer rotation (30 to 50 years or more) may ensure sustained wood production without compromising site productivity (Anderson & Ingram 1993).

Implications on sustainability of short rotation forests

The forest policy of India stresses the need to intensify afforestation and social forestry programmes on denuded, degraded and unproductive lands. Under various constraints of social forestry, managers have to augment the supply of fuelwood and fodder for the rural poor. As evident from past studies, nutrient contents are highest in leaves, twigs and branches. Short rotation extractions of fuelwood and fodder would mean nutrients are drained from an already degraded ecosystem. Sustainability in context of restoration forestry implies the maintenance and/or enhancement of organic matter build-up in the soil via photosynthetic accumulation and its return to the soil via litter fall. Therefore, removal of these nutrients from the site is potentially hazardous for the reclamation process. The previous recommendations to convert plantations on degraded soils for other production systems stem from the socio-economic constraints of private landowners to regain degraded agricultural land as soon as possible. Hence, management options that will maintain some tree cover on the land (i.e. alley cropping) need to be explored. This system may involve selective row thinning at an early age (15 to 30 years), leaving the residual trees for soil amelioration and protection. The cut strips provide corridors for agronomic production. This system takes advantage of incorporating juvenile, nutrient-rich branches, leaves and twigs into soil that contribute to sustained future crop production. Thus, if long-term maintenance of soil productivity is the object of forest restoration, then concessions given to rural poor must be reviewed cautiously and the rotation period must be greater than the minimum period of nutrient recovery. Moreover, the generally adopted clear felling system not only results in abrupt microclimate change but also exposes the soil to erosion and denudation. Some suitable felling system needs to replace the clear-felling practice on the reclaimed sites.

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