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Biotechnology policy series

Bioremediation, an environmental remediation technology for the bioeconomy

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Bioremediation differs from other industrial biotechnologies in that, although bioremediation contractors must profit from the activity, the primary driver is regulatory compliance rather than manufacturing profit. It is an attractive technology in the context of a bioeconomy but currently has limitations at the field scale. Ecogenomics techniques may address some of these limitations, but a further challenge would be acceptance of these techniques by regulators.

Bioremediation looks unlike any other biotechnology

Bioremediation refers to the use of biological processes for the clean-up of contaminated land and water, usually groundwater. There are several technologies in common use, divided broadly between *ex situ* and *in situ* methods (Figure 1). *Ex situ* technologies usually involve the construction of windrows or biopiles, either on site or at a remote location. *In situ* technologies are much less obtrusive, involve significantly fewer earthworks, but also require longer treatment times and suffer from a lack of control compared to *ex situ* technologies.

Scale of the contaminated land and water challenge

According to the European Environmental Agency (EEA), it is estimated that, in Europe, potentially polluting activities have occurred at about 3 million sites, of which, >8% (or nearly 250 000 sites) are highly contaminated and need to be remediated, and the total number of contaminated sites needing remediation may increase by >50% by 2025 [1]. In fact, the scale of the problem is as yet not properly identified. Meanwhile, remediation is progressing relatively slowly: in the past 30 years, only about 80 000 sites have been cleaned up (in those countries that collect data). Thus, with the current level of remediation activity, the problem is growing, not shrinking.

Groundwater contamination is more of a hidden problem because, unlike soil, it is unseen. However, the scale of its importance is worth highlighting. As many as 2 billion people rely directly on aquifers for drinking water, and 40% of the food in the world is produced by irrigated agriculture that relies largely on groundwater [2]. At least 12 mega-cities (populations >10 million) could not function without groundwater. China alone has >500 cities, and two-thirds of the water for them comes from aquifers. Despite this importance, the number of instances of groundwater contamination due to accidental spillages or unsatisfactory disposal is probably beyond counting.

Complacency over soil as a resource, or lack of finance?

Perhaps one of the reasons for this slow rate of contaminated land clean-up is a degree of policy and societal complacency. Soil, for example, is virtually ubiquitous, and to the casual observer it appears an almost infinite resource. There is an essential need to preserve soil for the future, especially since bioeconomy strategies call for increasing use of land for purposes other than growing food. In the bioeconomy and sustainability context, soil accounts for some 20% of the capture of human CO_2 emissions [3], but its slow rate of formation means that soil should be treated as a nonrenewable resource. It takes centuries to create a mere centimetre of soil but, if mistreated, soil can be destroyed very quickly. Soil degradation is accelerating and this is exacerbated by unsustainable human activities; one of them being soil contamination.

Increasingly central to urban planning is the redevelopment of brown field sites, that is, derelict or contaminated sites; often now in inner city or suburban locations. Although many communities have started to realise the economic opportunities that derive from recycling brown fields into productive land, few have taken full advantage of the potentially enormous social, environmental, and economic opportunities that can accrue from using these sites to enhance green space and infrastructure [4]. Redeveloping brown field sites, of course, decreases pressure on green field sites, which has implications for a bioeconomy, where the preservation of fertile agricultural land for food production is essential, whereas remediated brown field sites might also be suitable for the production of biomass.

Can we place an economic value on soil and soil services?

Valuing of soil ecosystem services is contentious and currently absent at the policymaking level. Available estimates of the value of such services – as flawed as such estimates may be – are very large indeed. For example, in 1997, the overall market and nonmarket values of all ecosystem services was estimated to represent a total intrinsic economic value of twice the total global gross national product (GNP) [5], and the services related to

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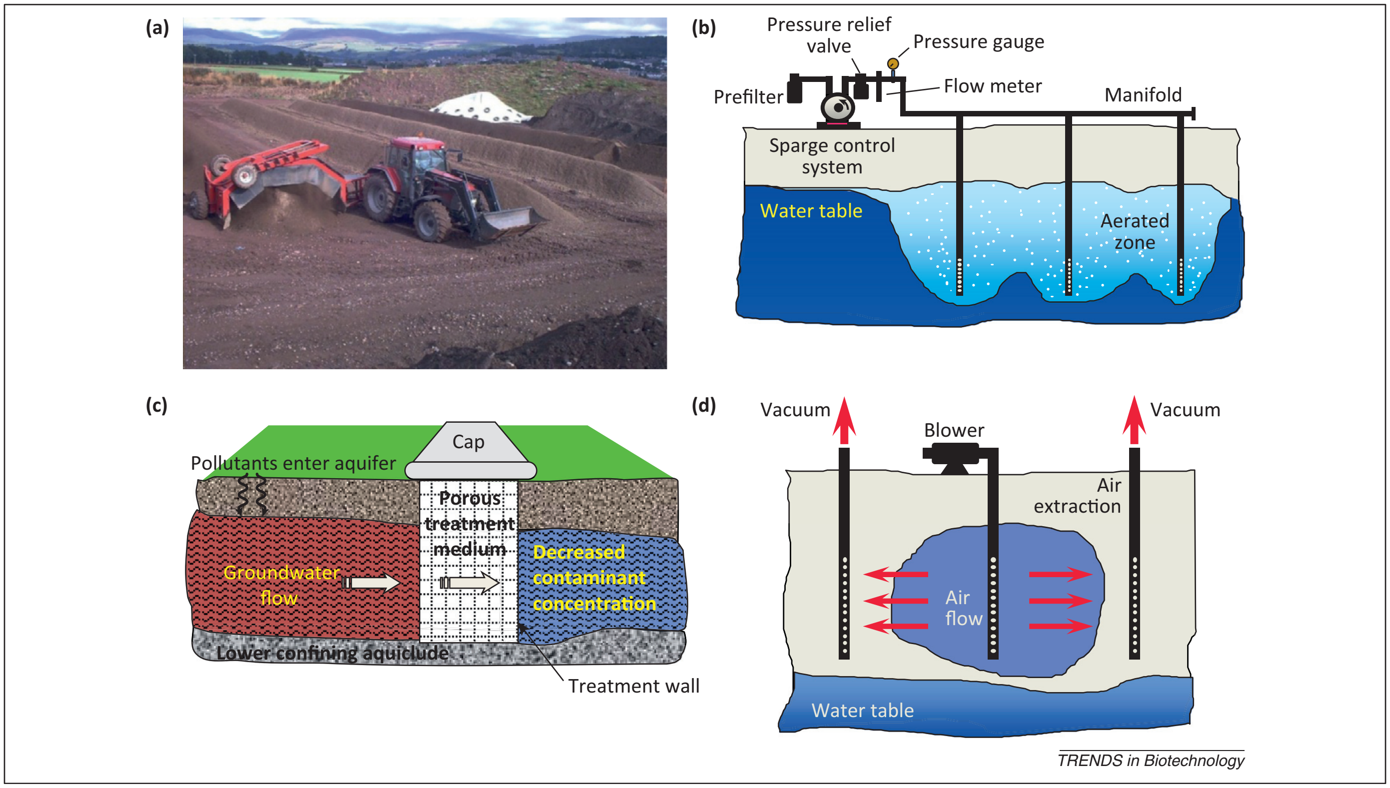

Figure 1. Bioremediation systems. **(a)** *Ex situ* treatment windrows being turned. Specially constructed windrow turners, either free-standing or tractor-powered, are used to turn soil periodically. This aids mixing and, crucially, aeration of the soil. (Reproduced, with permission, from Environmental Reclamation Services Ltd, Glasgow, UK) **(b)** *In situ* biosparging. During air sparging, air is injected into the saturated zone, usually below the target clean-up zone. Volatile compounds dissolved in the groundwater and sorbed on the soil particles will partition into the air phase and be transported to the vadose zone. The volatilised compounds can then be biodegraded by indigenous microbes. **(c)** *In situ* bioreactive barrier. The permeable reactive barrier (PRB) is an interception technology for the remediation of contaminated groundwater. It is installed across the flow path of the groundwater, and is constructed from porous materials, so that the water can pass through the wall. A short leap of the imagination, then, has led to attempts to create deliberately biological permeable reactive barriers, which Kalin [16] has termed passive bioreactive barriers. This technology is still in development. **(d)** Bioventing. Bioventing is a process that uses enhanced oxygenation in the vadose zone to accelerate contaminant biodegradation. This technology is also highly effective when paired with biosparging.

healthy soils in industrialised countries was valued at around €10 000 per inhabitant per year in 2010 [6]. In the EU, the annual cost of soil degradation alone is estimated at some €38 billion [1]. The overall message is clear – our society is utterly dependent on maintaining the global stock of healthy soil. Any plans for a future bioeconomy dare not ignore this. An increasing rate of soil degradation must be reversed.

Research and bioremediation practice

Bioremediation is used for site clean-up in approximately 10% of applications [7]. Given that it is a technology that may improve the quality of soil and appears more sustainable than other remedial technologies (such as incineration, which offers great certainty in treatment, but completely destroys the soil), this figure seems surprisingly low. This is principally due to a still widespread perception that bioremediation is a remedial technology that is: less reliable than others; difficult to predict in terms of the rate and extent of remediation (in particular whether specified end-points will be realised); and that requires more extensive, intrusive, and therefore expensive, site assessment. This does not generate confidence for stakeholders, especially land developers and regulators. There are broadly two ways that laboratory research may be directed at these problems.

Genetic modification (GM)

GM technologies have been used on many occasions to try to improve the rate of biodegradation of particularly recalcitrant organic pollutants. However, bioremediation of contaminated sites goes far beyond biodegradation in complexity (Figure 2), and is not amenable to the typically reductionist approaches (e.g., one compound, one strain, and one pathway) that have come to dominate biodegradation studies [8]. The major problem encountered in successful bioremediation technology using GM bacteria pertains to hostile field conditions for their survival [9]. Thus, in those specific instances where GM bioremediation agents may be warranted, despite the possibility that they might deliver environmental benefits and help diffuse some of the political angst around the use of GM, little is known about their efficacy in real clean-up situations.

Advent of -omics technologies

A plethora of genome-wide (-omics) technologies, biosensors, and community profiling techniques are available that could act as enabling technologies, so-called ‘ecogenomics’, to improve bioremediation in the field. Ecogenomics approaches could be used to characterise contaminated sites and monitor the bioremediation process [10]; especially those sites with recalcitrant and numerous pollutants. Bioluminescence-based bioavailability