Chapter 1
Bioenergy Crop-Based Ecological Restoration of Degraded Land

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Abstract Increasing land degradation worldwide asks for restoration solutions that are often multi-purposed by nature. Establishment of Bioenergy crops, such as perennial grasses and short-rotation woody crops offers possibilities for both successful eco-restoration of various marginal lands and energy production. Besides many recognized benefits in terms of increased soil carbon stocks, reduction of GHG gasses and economical gains, there are still many potential challenges in bioenergy crop cultivation and production, particularly in terms of negative environmental implications. Comprehensive scientific studies are trying to recognize and overcome their existence and scope. Creation of sustainable bioenergy crops-based ecosystems on the various types of degraded lands through affordable restoration approach could pose a challenging task, but by its realization the fractional intentions of several UN-SDGs can be achieved.

Keywords Biofuel crops · Eco-restoration · Degraded soil · Polluted land · Waste dumpsites

1.1 Introduction

Land degradation presents one of the marked global issues of modern times. Not only that it impacts the environment, agricultural production, livelihoods and safety, but also causes a long-term effect on ecosystem services and human health. Land degradation is recognized as a complex phenomenon. However, owing to this complexity, there is still no unique definition of the term "land degradation", and interpretations vary according to the discipline there are oriented to and main factors taken into

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account. For instance, Olsson et al. (2019) refers to land degradation as “a negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans”. Nevertheless, not every loss of productivity should be observed as land degradation, only the one characterized as persistent reduction of biological or economical productivity of land (Millennium Ecosystem Assessment 2005).

Other definitions use a more narrow approach. The United Nations Convention to Combat Desertification (UNCCD 1994) defines the term as “the reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or rangeland, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (a) soil erosion caused by wind and/or water; (b) deterioration of the physical, chemical and biological or economic properties of soil; and (c) long-term loss of natural vegetation”, referring it especially to the degradation of the dry lands, known as desertification. Land degradation results in the reduction of the ecosystem services as a consequence of human activities or natural processes (ELD Initiative 2013). Common ground of more frequently used definitions is that the term refers to the long-term loss of functionality and productivity of all components of the land (considered as system comprising of soil, landscape, terrain, water, climate, biota etc.) (Eswaran et al. 2001). International efforts to standardize the terminology and develop universal, widely accepted definition of land degradation are still ongoing.

Global land degradation—Increasing nature of land degradation and its spreading among world biomes has called for the assessment of this problem on global scale. Global efforts to address land degradation arose in the 1980s, calling for common action of decision and policy-makers from local to global level. This resulted in international agreement named the United Nations Convention to Combat Desertification (UNCCD), established in 1994 with the aim towards the reduction of land degradation and desertification in all participant countries affected. Additionally, United Nations recognized the need for urgent halting and reverses the land degradation by compensation through land improvement, putting the Land Degradation Neutrality (LDN) concept in force by Rio 20+ outcome documents and establishing it as one of the targets in Sustainable Development Goals. Land Degradation Neutrality concept addresses the need to maintain and, where possible, restore land and soil quality aiming to achieve a land-degradation-neutral planet (Caspari et al. 2015). The effective implementation of these international policies into practice requires spatial information on degraded lands, supported by the recognition of causes and responses of natural and social surrounding.

As land degradation must be estimated taking into account its spatial, economic, environmental and cultural context, evaluations of such complex issue turned out to be a challenging task (Warren 2002). While certain land degradation assessments evaluate soil parameters, others use vegetation assessment or assessments of net primary productivity. Earlier assessments were based on extrapolation of local assessments, while modern approaches include usage of remote sensing technologies

(Dubovyk 2017). Estimation of global degradation range varies between 15 and 63%, but majority of assessments agglomerate around 25–30% of degraded land on global level (Safriel 2007). In order to overcome misinterpretations due to the differences in definitions of the term "land degradation", scenarios for the UNCCD's Global Land Outlook (that aim to predict changes in land use under alternative development scenarios up to 2050) were developed by using the concept of "land condition" and by quantifying changes in key trends of land use and ecosystem functions to determine anthropogenic impact in relation to the natural state (Van der Esch et al. 2017).

Reasons behind land degradation—Land degradation involves both natural ecosystem and the human social system, and changes in both biophysical natural ecosystem and socioeconomic conditions will affect the land degradation process (Millennium Ecosystem Assessment 2005). Certain causes were, however, identified as driving ones: biophysical causes (e.g. topography and climatic conditions) and non-sustainable land use practices (deforestation, urbanization, habitat fragmentation, improper agricultural practices and others) (Li et al. 2015). There are also indirect and not so obvious causes of land degradation, predominantly in the form of triggers for application of non-sustainable land use practices, such as: poverty, population density, migration, economic development, urbanization, agricultural extension etc. As the land degradation usually results from a complex effect of several causes, the clear separation between direct and indirect drivers can sometimes be difficult. Research by Song et al. (2018) on global land change in period 1982–2016 has shown that 60% of all land changes are associated with direct human activities, and 40% with indirect drivers. Network of Sustainable Land Management (SLM) specialists called World Overview of Conservation Approaches and Technologies (WOCAT) has defined six main categories of land degradation, according to the prevailing degradation process: soil erosion by water; soil erosion by wind; chemical soil deterioration; physical soil deterioration; biological deterioration; and water degradation (Harari et al. 2017). It has been generally recognized that key mechanisms behind land degradation include physical, chemical and biological processes. Some of the most important physical processes are erosion, compaction, sealing and crusting and certain types of environmental pollution. Important chemical processes are acidification, salinization, leaching, loss of fertility etc., while biological processes include reduction in total soil carbon and biodiversity loss (Eswaran et al. 2001). However, social, economic and political causes are often the main driving forces behind current land degradation processes.

Impact on ecosystem services and livelihoods—Land degradation is affecting ecosystem services in many areas of the world. Moreover, degradation could be considered as persistent reduction of ecosystem services. Such services are interconnected with changes in land use, and more research on clarifying the type and degree of that connection are needed (Hasan et al. 2020). However, it is clear that land use change is affecting main types of ecosystem services (as defined by Millennium Ecosystem Assessment 2005): supporting services (biomass and oxygen production, soil production, nutrient cycling etc.), provisioning services (food, fresh water, timber etc.), regulating services (climate regulation, carbon sequestration, waste decomposition, water purification etc.) and cultural services (recreation, visual effects, physical and mental health benefits, spiritual experiences etc.). Those services are dynamically interrelated, but a land use change that is orientated towards prioritizing certain ecosystem service may eventually result in decline of other, non-prioritized ecosystem services (Millennium Ecosystem Assessment 2005). Analyses of the cost of land degradation among the types of ecosystem services showed that 54% of the cost refers to the losses in supporting, regulating and cultural services, belonging to public goods. In addition, 42% of the world's poor population depends on services of degraded lands for providing food and income (Nkonya et al. 2016).

Land degradation followed by loss of ecosystem services impacts the livelihood security of people, including food and water security and climate change. These effects are especially pronounced among most vulnerable society groups, particularly those living in rural areas (IPBES 2018). Land degradation shows an asymmetric impact across the society, increasing poverty and deepening inequalities among various income groups. It is found that land degradation could have increased severe rural poverty rates by almost 10% between 2001 and 2015, if other factors held constant (Global Mechanism of the UNCCD 2019). As land resources influence livelihoods of population that depends on them, application of sustainable land management practices could be the way to avoid the land degradation, especially in more affected parts of the world (Gashu and Muchie 2018).

1.2 Suitability of Bioenergy crops for Wide-Ranging Degraded Lands

Land degradation contributes to the emission of greenhouse gases (GHG) and reduced carbon uptake by the land (Olsson et al. 2019). It is estimated that certain changes in land use, such as deforestation and expansion of agriculture contribute to approximately 15% of global emissions of GHG (United Nations Department of Economic and Social Affairs, United Nations Forum on Forests Secretariat 2021). One of the land management strategies that could contribute to combating the land degradation and simultaneously provide carbon sequestration is establishment of bioenergy crops (plants grown for the purpose of energy production), namely perennial grasses and short-rotation woody crops. Advantages of growing crops for bioenergy include absence of negative impact on the carbon dioxide balance in the atmosphere and reduction of GHG emissions. As the amount of quality land suitable for cultivation is a limited resource, marginal lands were recognized as viable option for growing Bioenergy crops. Such marginal or degraded lands that are unsuitable for food production include various erodible, acidic, saline and contaminated soils, reclaimed mine soils, urban marginal sites and abandoned or degraded former agricultural land. As stated by Shortall (2013), marginal land is the type of land that can be classified as unused, free, spare, abandoned, under-used, set aside, degraded, fallow, additional, appropriate or under-utilized land. Moreover, growing energy crops on such lands could even enhance ecosystem services, as they can reduce erosion processes, restore contaminated land and improve overall biodiversity of the area (Valcu-Lisman et al. 2016).

Biomass production on different categories of marginal lands is variable and depends on the characteristics of a particular site, applied land management practice and selection of suitable plant species for this purpose. Various research showed that biomass yields may range between 1 and 14 Mg ha^{-1} for perennial warm-season grasses and between 0.5 and 9.5 Mg ha^{-1} for short-rotation woody crops, while soil carbon sequestration rate may vary between 0.24 and 4 Mg C ha^{-1} yr^{-1} (according to Blanco-Canqui 2016).

Perennial grasses are characterized by higher yield potential in comparison to the annuals. Moreover, warm-seasonal C4 perennial grasses can provide higher annual biomass yield at the higher temperatures as they possess more efficient photosynthetic pathway than C3 plants. Due to the characteristics of their active underground organs, perennial plants are effective in recycling nutrients, therefore exhibiting a lower nutrient demand than the annuals (Santibáñez Varnero et al. 2018). Besides, perennial grasses are tolerant to many abiotic stresses (Ranđelović et al. 2018), adaptable to the range of habitats and suitable for multiple uses (Pandey and Singh 2020). Some of the most suitable perennial grasses for purpose of growing bioenergy crops over the globe are: switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus* × *giganteus* Greef et Deuter), reed canary grass (*Phalaris arundinacea* L.), giant reed (*Arundo donax* L.), common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) etc. (Sanderson and Adler 2008; Scordia and Cosentino 2019).

Woody Bioenergy crops, also called short-rotation woody crops, are fast-growing trees that can reach high yields, tolerate conditions of various soil types and require low inputs. In comparison to majority of annual crops, they have a lower impact on soil erosion and increased nutrient and organic matter input to the soil (Whittaker and Shield 2016). Although short-rotation woody crops have longer harvest rotations than the perennial crops, they compensate it by production of higher yields. Short-rotation woody crops are mainly represented with species such as poplars (*Populus* sp.), willows (*Salix* sp.), eucalyptus (*Eucalyptus* sp.), nettlespurge (*Jatropha curcas* L.), sycamore (*Plantanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.) etc. (Lemus and Lal 2005; Pandey et al. 2012a; Pleguezuelo et al. 2015).

Results generated from investigation of growing energy crops on various types of marginal lands showed that the performance of various plant species were site-specific and species-specific (Blanco-Canqui 2016; Acharya et al. 2019). In order to reveal the potentials of bioenergy crops to grow on different categories of marginal lands a catalogue of crops suitable for growing conditions on different marginal lands in the territory of Europe was formed (SEEMLA 2016).

Perennial plants have demonstrated potential to be successfully grown on highly eroded lands, as they tend to form dense biomass cover in short time, and deep root system too. If used as conservation buffers in a landscape, such as hedges, filter strips or riparian buffers, these plants could successfully reduce wind or water erosion, therefore combining soil conservation practices with growing bioenergy crops (Kreig et al. 2019). Additionally, improved water quality in terms of reduced nitrogen and soil erosion rate in water can be generated by applying changes in cropping patterns and management practices of perennial crops (Valcu-Lisman et al. 2016). In addition, both wooden and perennial crops could be successfully established on steep slopes terrains and minimize soil erosion rates from such sites if good agricultural practices with minimal soil disturbances are applied (Jankauskas and Jankauskiene 2003).

Establishing energy crops on moderately polluted sites such as post-mining areas could be both economically viable and environmentally sound practice for simultaneously usage of biomass as energy source and improvement of the soil conditions. Coupling the phytoremediation with energy crops is another benefit that could be potentially gained on contaminated sites. Perennial grasses inhabiting post-mining sites are often recognized for their tolerance to metal toxicity as well as other characteristics of those sites, such as extreme pH values, sandy texture and low nutrient content (Ranđelović et al. 2014; Jakovljević et al. 2020). Similarly, certain tolerant woody species are also capable of growing at such sites (Migeon et al 2009; Shi et al. 2011). Naturally colonizing vegetation should preferably be used for this purpose in so-called sustainable phytoremediation approach (Pandey 2015), especially if it can contribute to the safe immobilization of the pollutants from contaminated sites. Selected plants should, however be preferably perennial, stress-tolerant, unsavoury to livestock, and able to generate both economic and ecological benefits for the site (Pandey 2017).

Formation of short rotation woody plants plantation on former mining sites is additional way to utilize biomass from mine lands. Performance of common energy crops that can be suitable for phytoremediation of various pollutants, such as *Miscanthus* × *giganteus*, *J. curcas, Salix* sp., *P. virgatum, A. donax* etc. was investigated for both purposes (Pandey et al. 2012a; Skousen et al. 2012; Jeżowski et al. 2017; Pandey 2017; Castaño-Díaz et al. 2018). The addition of soil amendments and microbial agents could additionally enhance the growth and yields of selected plants (Pogrzeba et al. 2017; Andrejić et al. 2019).

Saline soils, considered to be marginal lands of low productivity, are colonized by halophyte plant species that are able to thrive in saline conditions. Identification of suitable halophytes for biomass and energy production is currently in progress. Some plant species, such as *Desmostachya bipinnata* (L.) Stapf, *Kosteletzkya pentacarpos* (L.) Ledeb, *Salicornia bigelovii* Torr., *Tamarix jordanis* Boiss. etc. were recognized for their characteristics potentially suitable for energy production (Abideen et al. 2011; Bomani et al. 2011; Moser et al. 2013; Santi et al. 2014). Certain halophytes accumulate salts in their organs, which may generate problems during combustion or other biomass utilization processes, so halophytes with ability to exclude salts are generally considered to be a better choice for energy production (Sharma et al. 2016). However, before wider application of halophytes, hybridization and breeding should be conducted for domestication of wild species and their adaptation to agricultural management measures in order to obtain species with high yields and higher salinity thresholds, especially during the phase of germination and seedling emergence (Gul et al. 2013).

Wet and flood-prone marginal lands are also potentially suitable sites for growing dedicated energy crops. Das et al. (2018) investigated perennial bioenergy crops on wet marginal lands where soil properties and a biomass of switchgrass (*P. virgatum*) have been influenced by moisture gradient of the field. Barney et al. (2009) found that selection of adequate ecotypes of switchgrass for growing in excess soil moisture conditions could increase the range of environments suitable for growing Bioenergy crops. Similarly, short-rotation woody species such as willow or poplars that are naturally growing in floodplains and show ecological adjustments to the flooding conditions could be used as energy crops on such sites. However, although they are tolerant to wet conditions and can maintain efficient growth and productivity in such conditions, prolonged inundation could ultimately reduce their feedstock quality and increase the cost of the exploitation process (Bardhan and Jose 2012).

Using abandoned agriculture lands for bioenergy crops represents additional option for energy production on marginal lands. It has been estimated that bioenergy production on abandoned agricultural lands could satisfy approximately 8% of global energy demands (Campbell et al. 2008). Although there are still concerns about feasibility of using such sites and investigations showed that growing conventional crops on these lands as a bioenergy feedstock could potentially increase erosion rates and polluted runoff, field studies with low-input high-diversity mixtures of native perennial grasses grown for bioenergy purposes showed reduction of these impacts (Tilman et al. 2006). Projections of environmental implications on abandoned agricultural lands from production of bioenergy crops in subtropical region of Australia revealed that environmental improvements could be gained in open grazing areas, by using native woody perennial bioenergy crops under low management intensity, while other options did not produce favourable environmental outcomes (Miyake et al. 2015). However, there are indications that, if properly addressed, inclusion of perennial bioenergy crops on degraded parts of agricultural lands could create benefits in the landscape function and resilience and enhance ecosystem services such as wildlife habitat, soil and water quality (Blanco-Canqui 2016).

Additional research is required on the adequate utilization of various marginal lands for energy production with attention focused on selection of dedicated crops, such as extremophile energy crops. These crops would be adapted wild species or genetically modified existing crops that are capable of growing in extreme environments while retaining high productivity and low nutrient and water requirement (Bressan et al. 2011).

Growing energy crops on marginal lands becomes a field of intensive research and field trials. However, great care and careful planning are needed, as intensive management and exploitation measures on degraded lands could have negative impacts on soil, water and biodiversity conservation (Bonin and Lal 2012). Shifting marginal lands to bioenergy cultivation process should be carefully addressed in order not to cross certain thresholds by intensity of land use and compromise ecosystem services and biodiversity of such lands (Hennenberg et al. 2010). It is recognized that unsustainable bioenergy crop expansion could pose threat to biodiversity and habitats and could additionally degrade natural areas (Millennium Ecosystem Assessment 2005). Therefore, it should be secured that no land of conservation value or with significant carbon stocks is converted to biomass for energy production. European Directive 2009/28/EC on the promotion of the use of energy from renewable sources poses such requirements for sustainable biomass production, where bioenergy crops should not be obtained from land with high biodiversity value; land with high above ground or underground carbon stock and from peatlands. Biomass production should be environmentally responsible and any negative trade-offs for biodiversity, the environment and local communities should be avoided (Hennenberg et al. 2010).

1.3 Plant Derived Bioenergy Sources

Biomass is the renewable source of energy. Some sources of biomass are agricultural crops, algae, annual, perennial grasses or woody plants etc. Plants are producing biomass via photosynthesis, using sunlight energy to convert carbon-dioxide and water to carbohydrates and oxygen. Type and the amount of bioenergy that could be produced depend on the characteristic of biomass. Plants can be used for bioenergy production in two main ways: as energy crops (explicitly grown for that purpose) and as biomass residues (originating from plants grown for other purposes). Additionally, biomass can be converted to energy directly (by direct combustion) or indirectly (by conversion of row biomass material to fuels that are afterwards used for the energy production). Conversion of biomass to energy can be done thermochemically (by pyrolysis, combustion or gasification), biochemically (by using microorganisms and enzymes via technologies such as anaerobic digestion and fermentation) or chemically (use of chemicals to convert biomass to liquid fuels). These conversion technologies enable production of heat, power and biofuels. Besides, biomass it is the only renewable energy able to be processed into solid, liquid and gaseous fuels (World Energy Council 1994).

The production of heat is the leading modern bioenergy application throughout the world (WER 2013). Biomass efficiency for heating purposes depends on the plant chemical composition, especially the share of lignin (averagely 10–25 wt%), cellulose (40–50 wt%) and hemicellulose (20–40 wt%) (McKendry 2002). Relative proportion of cellulose and lignin is of particular importance for identification of plants suitable for energy crops, and their biomass is also known as lignocelluloses biomass. Some of the most important properties for biomass conversion process are calorific value, moisture and ash content, fixed carbon and alkali content. Biomass of perennial grasses generally shows higher contents of lignin and cellulose compared to the biomass of annual crops (Brown 2003). Generally, lignocellulosic biomass of woody species has higher contents of cellulose and lignin, while biomass of perennial grasses contains more hemicellulose and ash, making it less suitable for the combustion process (Scordia and Cosentino 2019). Among perennials, C3 plants have higher ash content in comparison to C4 plants (Zhao et al. 2012). Similarly, low moisture content woody and perennial species are more convenient for heating purposes, as higher water content has negative impact on biomass calorific value (SEEMLA 2016). Compacted forms of biomass such as wood pellets and briquettes can also be used for combustion. Short-rotation coppices of willow and poplar present the opportunity for sustainable source of biomass for such purpose. Moreover, high variation and presence of diverse cultivars among this species offer choices for optimizing the feedstock quality. However, the increased demand for heating sources is driving for more non-woody biomass resources (e.g. perennial grasses) to be used for this purpose (Santibáñez Varnero et al. 2018), and although their heating properties is usually lower than of woody biomass (Gami et al. 2011), they could provide sustainable amounts of feedstock due to their high biomass production.

Variety of liquid and gaseous fuels can also be produced from plant feedstock. Depending on the source of biomass, biofuels may belong to "first generation" (derived from food crops) and "second generation" (derived from lignocellulosic biomass of energy crops, including woody crops and perennial grasses). Most common liquid biofuel types are biodiesel and bioethanol. Among the gaseous fuels biogas (consisting of methane and carbon-dioxide) is the most commonly produced.

Bioethanol is considered to be an alternative to fossil fuels (especially petrol). Although technology for producing ethanol from food crops has been well developed and practically applied, competition with food sources has begun to be the issue of concern. Therefore, lignocelluloses biomass has recently gained attention as a source for bioethanol production. Research shows that net energy balance (energy in versus energy out) is generally lower in bioethanol gained from lignocelluloses materials in comparison to ethanol produced from sugar and starch-based feedstocks (Hayes 2008). There is ongoing research to identify plants suitable for bioethanol production, usually among ones with enhanced biomass production, such as *P. virgatum*, *P. arundinacea*, *Miscanthus* × *giganteus, A. donax* and others (Taiichiro and Shigenori 2010). Moreover, a significant portion of the research is dedicated to the use of woody species for production of bioethanol, especially fast-growing ones such as poplars and willows (Huang et al. 2009; Wang et al. 2011; Littlewood et al. 2014). Efficient and economically viable production of bioethanol from lignocellulose biomass depends primarily on the development of a suitable, simple and cost-effective pretreatment system for making cellulose from biomass accessible to the enzymes that break carbohydrate polymers into simple sugars available for further fermentation (Wi et al. 2015; Porth and El-Kassaby 2015). As the biomass composition of energy crops differ, individual approach in development and selection of suitable processing methods is needed for making bioethanol economically sustainable (Raud and Kikas 2020). Pilot plants established through the world demonstrated successful production of the bioethanol from agricultural waste, but the conversion of wood waste to bioethanol has turned out to be a challenging task (Johnson et al. 2009). Second-generation technologies using lignocellulose feedstock are still immature and need further development to demonstrate feasibility at commercial scale (Zhu et al. 2020).

An additional option for producing biofuels out of plant biomass is to extract the oils produced by plant seeds in a form of biodiesel. It is easy biodegradable fuel with potential to replace transportation fuels such as petroleum and diesel. Biodiesel is primarily generated by transesterification of plant oils. It is currently commercially produced from biomass of several species, such as canola, palm, rapeseed etc. Again, attention is paid to the potential use of lignocellulosic biomass for biodiesel production. *Jatropa curcas* was previously identified as one of the most promising species for biodiesel production, due to the stated high yields and 40–60% of oil content in seeds (Koh and Ghazi 2011), as well as the energy value of seed oil that was higher than in some types of coal (Wahyudi et al. 2019). However, grown in various field conditions, *J. curcas* generally did not meet the expectations due to the high fluctuation of yields, susceptibility to pests and diseases and toxicity of the seed cake (Moniruzzaman et al. 2017). Another non-edible plant potentially suitable for biodiesel production is *Pongamia pinnata*, whose seeds are found to contain 35% of oil, while fuel properties were found to be close to that of high-speed diesel (Ahmad et al. 2009). Technologies for production of biodiesel from second-generation crops are still at the beginning and need certain advances concerning seed production, management of plantations, biodiesel processing technology and supporting policies.

Biogas is a renewable energy resource produced during anaerobic bacterial degradation of biomass. Several second-generation crops showed potential for methane production. Perrenials *P. arundinacea* and *Elymus elongatus* cv. "Szarvasi-1" exceeded methane yields under favourable conditions in comparison to maize (Schmidt et al. 2018). Similarly, *A. donax* has been proposed as a suitable energy crop for biogas production. Although its production of methane was less than that of maize, the higher biomass production led to much higher biogas yield per hectare (Corno et al. 2015). Research on biogas production from other non-edible crops in terms of technology, economic benefit and environmental effects could contribute to the enhanced use of the renewable energy sources.

1.4 Degraded Land Restoration by Energy Crops

Degraded lands are inappropriate for agricultural crop cultivation due to low productivity (Gelfand et al. 2013). Generally, degraded lands include sodic land, saline land, nutrient poor land, urban marginal land, polluted land, waste dumpsites like fly ash dumps, mined land, red mud dumpsites, etc. These degraded lands have an uncertain and insignificant contribution to food security due to biotic and abiotic complications. Land degradation is phenomena of great concern because day by day it is increasing over the world. Hence, the transformation of degraded land in self-sustaining energy ecosystem is a current demand that will provide life-supporting services and support climate change mitigation (Hobbs et al. 2014). It depends mainly on the adaptation abilities of energy crops on degraded land. Many studies are available in terms of suitability of diverse energy crops to perform on various types of degraded lands (often under different watering and fertilization regimes), as well as their potential for production of various fuels (Table 1.1). Additionally, a high share of research conducted on field scale enables insights in performance of energy crops in real conditions of degraded sites.

As anthropogenic influence on land is growing and is often followed by environmental pollution, it is of particular importance to study the potential of bioenergy crops grown on different types of contaminated lands. Content and state of both organic and inorganic pollutants in soil influence not only the plant growth and

Table 1.1 Various research studies on energy crops grown on different types of degraded lands

Energy crop	Degraded land type	Experimental conditions	Research target	References
Arundo donax	Fertile and marginal soils	Field study	Environmental impact of bioenergy crop cultivated on fertile and marginal land via Life Cycle Assessment	Bosco et al. (2016)
Arundo donax	Reclaimed mine sites	Field study	Characterization of biomass, biochar, bio-oil and non-condensable gases generated from plant grown on mine sites	Oginni and Singh (2019)
Arundo donax, Miscanthus × *giganteus*	Moisture soils, inundate soils	Greenhouse conditions	Access moisture stress tolerance, physiological stress, and biomass yields	Mann et al. (2013)
Atriplex nitens, Suaeda paradoxa, Karelinia caspia	Saline soil	Field study	Biomass yield, chemical characteristics of biomass, biogas production	Akinshina et al. (2014)
Eucalyptus globulus	Fertile and non-fertile, irrigated and non-irrigated soils	Field study	Evaluating factors that affect the economic sustainability of Eucalyptus production (yields, prices and costs etc.) on marginal lands	Acuña et al. (2018)
Jatropha curcas	Marginal soils	Field study	Potential for cultivation of plant as bioenergy crop via propagation and growth tests	De Rossi et al. (2016
Jatropha curcas	Abandoned agricultural land	Field study	Effects of irrigation systems with recycled wastewater on morphometric characteristics, plant growth and productivity, soil fertility status	Dorta-Santos et al. (2015)

(continued)

Table 1.1 (continued)

Energy crop	Degraded land type	Experimental conditions	Research target	References
Manihot esculenta	Contaminated site	Field study	Plant growth and remediation potential, bioethanol production	Shen et al. (2020)
Miscanthus × *giganteus*	Degraded coal mine soil	Field study	Effect of sewage sludge and sewage sludge with mineral fertilizer on plant height and biomass yield, changes of soil conditions	Jeżowski et al. (2017)
Miscanthus × *giganteus*	Saline soil	Control environmental glasshouse	Biomass yield and production, stress tolerance level	Stavridou et al. (2017)
Miscanthus × *giganteus*	Contaminated agricultural soil, post-military soil, petroleum contaminated soil	Field study	Calorific values of biomass	Nebeská et al. (2019)
Miscanthus × *giganteus*, *Phalaris arundinacea, Salix schwerinii* × *Salix viminalis*	Marginal land, brownfield sites, landfills	Field study	Biomass yield and contamination, fuel composition	Lord (2015)
Panicum virgatum	Marginal soil (podzolic)	Field study	Effects of cultivation technology and different types of cultivation systems on biomass yield	Taranenko et al. (2019)
Panicum virgatum, Populus × *hybrid*	Marginal land	Greenhouse, field study	Effect of soil microbes and seaweed extract on plants productivity	Fei et al. (2017)
Panicum virgatum, var. Shawnee and Carthage	Reclaimed mine sites	Field study	Effects of different fertilizer systems on biomass yield of selected plant varieties	Brown et al. (2015)
Phalaris arundinacea, Panicum virgatum	Wet marginal soils	Field study	Influence of moisture gradient on above-ground biomass yields	Das et al. (2018)

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Table 1.1 (continued)

Energy crop	Degraded land type	Experimental conditions	Research target	References
Pennisetum americanum × *P. purpureum*	Saline soil	Field study	Effects of mulching, plant density, and organic/inorganic fertilizers on biomass yield, plant height and soil microorganisms	Wang et al. (2014)
Populus nigra × *Populus maximowiczii* Henry cv Max 5, *Robinia pseudoacacia, Salix viminalis*	Marginal degraded soil	Field study	Assessment of survival rate, plant morphological traits and biomass yields by using different soil amendments	Stolarski et al. (2014)
Salix alba, Salix viminalis	Peat soil, alluvial soil, heavy clay soil	Field study	Accessing plant morphological traits and biomass yields	Stolarski et al. (2019)

biomass production, but also the quality of various derived energy sources. Many research studies have been dedicated to access the degree of plant contaminant uptake, or concentration of contaminants in final or by-products, such as oil, ash, or wood chips.

Some potential and perennial bioenergy grasses such as *Arundo donax* L., *Miscanthus* × *giganteus*, *Panicum virgatum* L. have been identified especially from Australia, Europe, and the United States for enhancing the contribution of bioenergy production at global level (Patel and Pandey 2020; Praveen and Pandey 2020; Alexopoulou 2018). For instance, *A. donax* and *Miscanthus* genotypes (*M.* × *giganteus*, *M. sinensis*, and *M. floridulus*) were tested on heavy metal contaminated soils, and results showed that the presence of trace elements reduced biomass production of investigated plants, while *M.* × *giganteus* kept the highest biomass production under conditions of Zn-contaminated soils (Barbosa et al. 2015). Additionally, analysis of percolated waters showed that *A. donax* promoted Phytostabilization of Cr, Zn and Pb in soil, and *Miscanthus* genotypes similarly prevented leaching of Zn in water, thus contributing to the overall remediation of the environment. Multiple studies confirmed tendency of *M.* × *giganteus* for retaining the majority of accumulated metals in its underground parts (Korzeniowska and Stanislawsk 2015; Pidlisnyuk et al. 2019; Andrejić et al. 2019), so low concentration of metals accumulated in above-ground organs should not be obstacle for its use as bioenergy crop. However, noted elevated contents of potassium in plant biomass associated with regulation of the metal exclusion as adaptive plant response could cause problems with

Fig. 1.1 Field trials with *Miscanthus* × *giganteus* on Pb–Zn–Cu flotation tailing site Rudnik in Serbia (photo by courtesy of Mr. Dželetović Željko)

fouling and slagging during combustion, so regulation of potassium content should be further investigated for making the combustion process more efficient (Laval-Gilly et al. 2017). Additionally, fuel characterizations of *M.* × *giganteus* biomass from a phytoremediation sites located in Poland and Germany showed differences in the thermal decomposition of biomass, possibly due to the differences in pH value and heavy metal content of the investigated soils (Werle et al. 2019). Moreover, performances of *M.* × *giganteus*, *M. sinensis*, and *M. sacchariflor*us were analyzed in different environments across Europe, showing significant influence of the environment on composition and quality of plant biomass (Van der Weijde et al. 2017). As such, environmental influence should be acknowledged when deciding the end-use of *Miscanthus* feedstock, as well as during development of novel varieties with improved biomass quality for biofuel production. *Miscanthus* spp. can generally be used for combustion, biofuel production and Phytostabilization (Figs. 1.1 and 1.2), bridging the environmental remediation and renewable energy production, so further investigations in terms of its utilization for such combined purpose are needed.

Similarly, *P. virgatum* was considered as model perennial energy crop, while at the same time its tolerance or capacity for removal of inorganic and organic contaminants from soils and water was recognized (Guo et al. 2019; Phouthavong-Murphy et al. 2020). Ability of *P. virgatum* to extract metals from contaminated sites was modelled by Chen et al. (2012), who developed different models between plant metal content and biomass yield for predicting the amount of Cd, Cr and Zn potentially extracted by plant. Obtained results suggested its use for Phytoremediation purposes, while acknowledging that the biomass yield is significantly correlated with uptake of metals. Cultivation of *P. virgatum* on Pb-contaminated soil for accessing its remediation efficiency and applying two conversion routes (enzymatic hydrolysis and fast pyrolysis processes) for biofuel production was implemented by Balsamo et al. (2015). Lead was mainly retained in the roots of *P. virgatum*, and the uptake rate increased with the Pb concentration in soil. However, Pb present in the biomass of *P. virgatum* from contaminated site had minimal or no effect on the fast pyrolysis

Fig. 1.2 Field trials with *Miscanthus* × *giganteus* on fly ash deposits of thermal power plant "Kolubara" in Veliki Crljeni, Serbia (photo by courtesy of Mr. Dželetović Željko)

processes and the following bio-oil products distribution in comparison to the plant biomass from control non-polluted site. Enzymatic hydrolysis with fungal cultures additionally showed that production of sugar by selected cultures was not adversely affected by the Pb content in *P. virgatum* biomass.

Besides those already mentioned, neglected and underutilized perennial grasses *Saccharum spontaneum* L. and *S. munja* Roxb. were also noticed for their potential to revegetate, remediate and restore fly ash dumpsites (Pandey et al. 2012b, 2015a; Pandey and Singh 2014; Pandey 2015, 2017; Pandey and Singh 2020), sponge iron solid waste dumps (Kullu and Behera 2011), coal-mined lands (Maiti et al. 2013) and rock phosphate mine restoration (Bhatt 1990). Thus, *Saccharum* spp. has been noticed as a potential bioenergy grass, but to date it is neglected and underutilized, and requires proper attention for exploitation of its unique characteristics for land restoration and bioenergy production (Fig. 1.3). Likewise, some other grasses such as *Arundo donax* L., *Desmostachya bipinnata* L. Stapf., *Panicum antidotale* Retz., *Saccharum* species, *Vetiveria zizanioides* L. are broadly dispersed over India and have abilities to grow naturally on degraded lands without outer inputs.

Various tree species were tested for their capacity to produce useful biomass and remediate contaminated sites. This is especially the case with short-rotation coppice crops of willows and poplars, but also the species such as *J. curcas*, *Alnus glutinosa*, *Eucalyptus* sp., *Robinia pseudoacacia* etc. Potential of willow species and their clones to accumulate metals such as Cd, Cu, Pb and Zn from polluted soils was recorded by various researchers (Tlustoš et al. 2007; Algreen et al. 2014; Yang et al. 2014; Lebrun et al. 2017). *Salix* genus is often used in short-rotation coppice system for energy production, showing fast growth and high biomass yields. A number of

Fig. 1.3 *Saccharum* spp. on fly ash disposal area of Renusagar thermal power plant, Renukoot, Sonbhadra district, Uttar Pradesh, India (photo by courtesy of Dr. Vimal Chandra Pandey)

clones and cultivars with improved traits enable wider use of willows for simultaneous Phytoremediation and bioenergy production. Positive results in removal of hazardous substances from various landfill leachates were reported in short-rotation willow coppice Phytoremediation systems used on large-scale in Sweden (Dimitriou and Aronsson 2005). However, to reach environmental and economic benefits, both biological and technical approach should be optimized. When biomass of *Salix viminalis* L. grown on contaminated dredged sediment disposal site was gasified in order to determine the fate of accumulated trace elements (namely Cd, Cr, Cu, Ni and Pb) upon the biomass conversion, gasification results showed that concentration of Cd and Zn in bottom and cyclone ash fractions exceeds thresholds for using the ash as soil fertilizer; therefore the ash originating from this process should be landfilled (Vervaeke et al. 2006). Optimization of gasification process would contribute towards concentrating trace elements in small ash fraction, so that the more voluminous fractions could be utilized in forms of fertilizer. The fate of the metals (Cd, Zn, Cu, Pb) present in the *Populus maximowiczii* × *P. trichocarpa* cultivar Skado grown on contaminated soil was studied in the end-products of the torrefaction and pyrolysis processes by Bert et al. (2017). Although concentration of accumulated metals in above-ground biomass was low, they were eventually concentrated in end-products. Similarly, content of metals would be a limiting factor in case of valorization of bio-oils from torrefaction and pyrolysis. Biomass of poplar from Phytoremediation site with contaminated soil was subjected to gasification experiments, where higher ash content and significantly lighter hydrocarbons in comparison to poplar from natural site were obtained, possibly due to the increased content of Ca and Mg that could act as catalyst in the tar (Aghaalikhani et al. 2017).

One of the recognized energy crops, *J. curcas,* was also investigated for its Phytoremediation ability. García Martín et al. (2020) found that *J. curcas* accumulates Fe, Cr, Cu, Mn, Ni and Zn in the aerial parts in higher concentration than in underground parts, thus exhibiting significant potential for metal Phytoextraction. Álvarez-Mateos et al. (2019) found reduction of 30–70% of Cr, Ni, Cu, Zn and Pb from mining site

Fig. 1.4 *Jatropha* spp. on fly ash disposal area of Tanda thermal power plant, Uttar Pradesh, India (photo by courtesy of Dr. Vimal Chandra Pandey)

soils, coupled with their higher transfer factors to shoots. Aggangan et al. (2017) tried to modify high transfer rate for Cu and Zn in *J. curcas* with mycorrhizal treatments. Upon the root colonization with investigated mycorrhizal inoculums Translocation of Cu and Zn to the aerial plant parts was inhibited and majority of elements were retained in roots of *J. curcas*. Moreover, concentrations of Cu and Zn in fruits and seeds remained below the detection limit, which enabled their further use for the production of biofuels. Similar biotechnological approaches coupled with selection of varieties with high seed oil content and yield could offer new possibilities for application of *J. curcas* in Phytoremediation of degraded lands. Besides accumulation of contaminants, additional reclamation benefits could be achieved, such as improved soil or water quality, increase of soil microorganism content and overall biodiversity at the site. *J. curcas* has been recognized for remediation and biofuel production (Fig. 1.4).

Eventually, to avoid environmental and health risks, end-products might be purified, or technology improved, allowing the use of metal-enriched plant biomass for efficient energy production. Distribution of metals in the end-products depends on the conversion process used, as well as from the optimization of process parameters. More research is needed in this sense in order to find viable solutions for conversion of biomass from remediated sites to bioenergy.

Leguminous plant-based biofuel production has also been reported and found suitable for land restoration because of their potential to enhance soil productivity owing to their connection with N_2-fixing bacteria, which is particularly suitable for various types of degraded sites and marginal lands. Suitable plants could be *Acacia mangium*, *Galega* sp., *Medicago sativa*, *Onobrychis viciifolia* and others (Singh et al. 2019). It has also been reported by da Costa et al. (2015) that energy yield of *A. mangium* grown in Amazon biome was two times larger than *Acacia auriculiformis,* including differences in biomass distribution. Density of this species as well as their calorific value in investigated area was increased in comparison to native species, revealing their potential for establishing energy forests. Additionally, *P. pinnata* is recognized as nitrogen-fixing tree species that produce oilseed and could simultaneously contribute to restoration of degraded lands (Leksono et al. 2018). *Galega* sp., *M. sativa* and *O. viciifolia* were found to store the higher N_2 content in their dry biomass that enhances the *C*:*N* ratio. The higher *C*:*N* ratio based leguminous plants are suitable for higher biogas production and may be used as an indicator to identify potential legume plant for more biogas production (Slepetys et al. 2012). It also assists to control Soil organic carbon by removal of residues, soil cultivation and land use change. However, a proper management of crop residues is needed to ultimately help to increase soil carbon and nitrogen stocks (Wu et al. 2018; Martani et al. 2020).

Environmental footprint of bioenergy crops depends on several factors, including the type of crop, land use and soil type. Important issue in bioenergy crop cultivation is their influence on soil properties, both short- and long-term, especially on degraded or marginal lands. In this sense, improvement of soil conditions in order to support sustainable yields and ecosystem services should be one of the main tasks in successful management for bioenergy. For example, the impact of introduced perennial bioenergy crops on soil quality showed positive effects on soil carbon pools, microbial and enzymatic activities, as well as activities of soil fauna (Emmerling et al. 2017). Similarly, bioenergy crops on contaminated agricultural sites showed increased diversity of soil fauna (Chauvat et al. 2014). Contrary to that, non-favourable changes in soil physical properties, such as decline of porosity and water infiltration rate, followed the conversion of reclaimed mine soil to bioenergy crop production site (Guzman et al. 2019). Quantifying change of soil parameters during land use change to bioenergy crops in different environments presents important task in which further research on small and large scales are needed.

1.5 Livelihood Improvements

Establishment of multiple energy cropping systems on degraded lands such as nutrient poor lands, polluted lands and waste dumpsites is a current demand to improve livelihood and to reduce environmental problems. Generally, the integrated assessments of bioenergy deployment should consider social dimension and livelihoods in more detail, as they are particularly important for practical implementation of bioenergy production. Government policy on biofuels should be intended to utilize degraded lands together with farmers, unemployed villagers, practitioners, companies, entrepreneurs, self-help groups, etc. Energy crop cultivation on degraded lands and especially nutrient poor land will help poor villagers by providing more ecological-resilient cash energy crops than traditional crops (Scordia et al. 2018). However, particular care should be given to promotion of programmes and communication with small-scale farmers on bioenergy production issues in order to avoid misunderstandings, particularly in the terms of expected profits and access to resources. The cultivation of energy cropping systems on degraded lands is labour-intensive and will provide job opportunities to local people including both skilled and non-skilled workers by various steps such as planting, harvesting, collecting, baling, densification, carrying, energy production (Mckendry 2002) and decentralized bioenergy systems such as processing and distribution (Valentine et al. 2012). On the other hand, agricultural residue of this system can be used for making compost and biochar. Besides the employment generation, these energy systems on degraded land will also help in climate change mitigation, promotion of local tourism and cultural activities. In India, wide-ranging driven policies (Bioenergy Policy, Green India Mission, MNREGA, Ethanol Blended Petrol Program, National Biodiesel Mission, Biodiesel Blending Program, etc.) can be linked with energy crop-based degraded land restoration. If energy crops should be used for restoration and remediation of marginal and contaminated lands, besides providing transparent and established values on cost-effectiveness of the process in order to create more realistic expectations, it is also important to simultaneously advocate remediation of human relationship with the land.

1.6 Potential Challenges

Although bioenergy cropping systems on degraded lands offer multiple benefits including ecological and socioeconomic aspects, there can be many potential challenges in their cultivation and production. First, the potential challenges of restoration of degraded lands are hostile conditions such as physicochemical and biological characteristics (i.e. low or high pH, heavy metals, metalloids, poor microbial activities, poor soil-nutrient status, higher temperature, water scarcity, etc.) that may not be suitable for growing bioenergy crops. Such scarce conditions may cause diverse effects, like yield reduction, accumulation of pollutants in plant tissues, plant metabolic disorders, reduction of vitality, occurrence of pest and diseases etc. However, as arising from previous examples, presence of contaminants in biomass of plants from contaminated sites may reduce the range of their final uses as energy crops. Therefore, combating impeding issues for each specific case of marginal land and optimizing the cropping systems in order to be most adapted to the site conditions is one of the future tasks and challenges in wider application of bioenergy crops.

The degraded land restoration is among the most important tasks for achieving UN-Sustainable Development Goals (UN-SDSGs). The challenge of degraded land's restoration could be solved through sound ecological restoration technologies implemented by skilled practitioners. In recent years, ecological restoration technologies are popularized as affordable and effective (Pandey et al. 2015b; Pandey 2017, 2021) for remediation and management of degraded land. They should particularly take into account plant species selection, climate changes, plant and soil carbon storage potential, planting density and technology, and application of maintenance measurements. If not done in a proper way by using optimal management practices, bioenergy production on degraded land could cause negative effects such as deterioration of water quality, soil erosion, nutrient depletion and increase in greenhouse gas emissions (Wu et al. 2018). It has been recognized that growing woody plants with or in rotation with herbaceous bioenergy crops could additionally improve both the soil properties and the crop yields (Schrama et al. 2014). Similarly, intercropping of perennials and legume plants could lead to the sustainable biomass production (Nabel et al. 2018).

However, bioenergy monocultures are certainly able to restore degraded lands, but on the other hand, they may decrease the biodiversity (Pandey et al. 2016). Second, it is of vital importance to correctly manage the bioenergy cropping systems; otherwise, their potential invasiveness can shift the native species (Pandey et al. 2016). For example, invasiveness of *Prosopis juliflora* in process of restoration of degraded lands in India showed reduction of local flora to much lower number of species in comparison to non-invaded areas (Edrisi et al. 2020). Monocultures of bioenergy crops, especially those growing in conditions of reduced landscape heterogeneity increase the potential for future invasion of non-native species, as in case of *P. virgatum* (Hartman et al. 2011). However, if the concept of bioenergy multi-cropping system is applied and diverse mixtures of suitable species are used, the biodiversity may be increased alongside with enhanced biomass production and ecosystem services (Awasthi et al. 2017).

More comprehensive scientific research concerning various species with potential of producing bioenergy in different locations and climatic conditions, as well as under various management practices are needed in order to gain better insights in real pros and cons of bioenergy production. So far, there are a limited number of Life Cycle Assessments conducted evaluating environmental costs in bioenergy production chain (Wu et al. 2018), which is of vital importance in addressing the environmental influence of such energy production type and its potential consequences.

1.7 Growing Bioenergy Crops on Degraded Lands: Achieving UN-SDGs

The utilization of degraded lands for good health and well-being of human is urgently required as well as the attaining UN-SDGs. However, the restoration of degraded lands is still the ambitious and tough task for the soil–plant scientists and practitioners. But recent advances in restoration technologies have significantly contributed to our ability to restore lost ecosystem services from degraded lands. Growing bioenergy crops on degraded land is gaining high importance in global land restoration programmes. UN Decade on Ecosystem Restoration (2021–2030) emphasizes such possibilities, coupled with sustainable ecosystem restoration practices.

Therefore, it is required to explore affordable and sustainable restoration technologies to achieve maximum UN-SDGs. Bioenergy crop-based restoration is gaining importance as affordable and sustainable approach in restoration programmes. Hence, it is vital to manage bioenergy multi-cropping system in such a way that the energy plant biodiversity can deliver life-supporting services towards the intentions of international policies (such as GHG emissions and soil organic matter sequestration). Otherwise, results may be deteriorating towards ecosystem functions, food security and biodiversity loss.

In developing countries like India, local villagers can be employed in bioenergy crops-based restoration programmes for accelerating the recovery of the degraded lands, thus increasing per capita income and reducing poverty. Plantation of multiple cropping systems of bioenergy crops on degraded lands significantly increases biodiversity that offers habitat to a surplus of flora and fauna species, provides ecosystem services, mitigates climate change, and reduces CO_2 emission and environmental pollution. Therefore, creating a sustainable bioenergy crops-based multifunctional ecosystem on the degraded lands through affordable restoration approach can achieve the fractional intentions of several UN-SDGs, especially those that address poverty (SDG 1), good health and well-being of people and societies (SDG 3), affordable and clean energy (SGD 7), decent work and economic growth (SDG 8), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15). Scientific contribution towards these goals is vital, as investigations of biomass sources and bioenergy products continue, coupled with field research concerning issues such as land use transition, soil and water quality, biodiversity and socio-economic effects.

1.8 Conclusion

Land degradation requires wider global attention, as well as the efforts to restore ecological functions of such lands. As bioenergy production is taking higher share in global energy consumption, matching these approaches in a way that could reach maximum UN-SGDs represents challenging scientific, societal and economic task.

During conversion of marginal and degraded lands into sites for growing bioenergy crops, many issues, such as land use changes, soil carbon and nitrogen content, GHG emissions, biodiversity, Water use efficiency, erosion rate, livelihood improvements and economical values of products should be considered. During efforts to reach sustainable bioenergy production it is of paramount importance to carefully address environmental issues and avoid unsustainable crop expansion in order not to cause deteriorate effects on soil and water quality, GHG emissions, biodiversity, erosion etc. Sustainable practices, such as using dedicated bioenergy crops, mixed cultures, rotation and intercropping and application of optimized agronomic practices can be beneficial to biodiversity, soil carbon and nitrogen content and GHG mitigation.

Various types of degraded lands require different approaches and management methods for overcoming obstacles in bioenergy crop production. Field studies revealed that performances vary depending on plant species used as bioenergy crop and site-specific conditions and limitations. Beside already recognized and widely studied bioenergy crops, there is a need to search for other, preferably multipurpose plant species, which could be additionally used for bioenergy production. Site limitations could also play crucial role in determining the success of bioenergy crops. For example, during restoration of contaminated marginal land it is important to access not only the growth parameters, but also the contamination level of final products in order to make them safe for bioenergy consumption.

Using Life Cycle Assessment tool for developing site-specific designs and applying sustainable management practices for producing bioenergy crops should aid in recognition of environmental footprints and bottlenecks for bioenergy production process on various types of degraded lands. Future scientific research should reveal still unknown mechanisms, behaviours and connections between various parameters in soil–plant-water systems of diverse degraded sites, especially in terms of their restoration under growing anthropogenic pressures in climate change conditions. Finally, wider social acceptance of bioenergy production through creating adequate policies and livelihood improvement that could be brought to producers, especially to local people in developing countries, is of great importance for implementing bioenergy production and should be responsibly promoted taking into account both advantages and potential disadvantages of this process.

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