Agricultural Systems 204 (2023) 103560

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Review

Concepts of agricultural marginal lands and their utilisation: A review

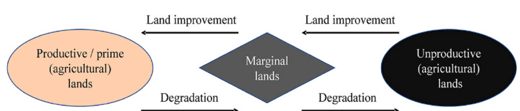
Nándor Csikós [a,*], Gergely Tóth [a,b]

[a] Centre for Agricultural Research, Institute for Soil Sciences, Department of Soil Mapping and Environmental Informatics, H-1022, Budapest, Hungary
[b] Institute of Advanced Studies, H-9730 Kőszeg, Hungary

HIGHLIGHTS

- Marginal lands are depending on the spatial scale and the regional conditions.
- Marginal land can be turned suitable for the objective of the use.
- Marginal lands are dynamic both in time and space.
- Flexible policy and practical solutions are needed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Marginal land
Agriculture
Land management
Concept
Marginal land review

ABSTRACT

CONTEXT: The potential of marginal lands to improve food security, support bioenergy production or ecosystem services has globally got a lot of attention. Defining agricultural marginal land is a task that involves more than just considering the land's quality, its definition changed a lot during the last two centuries.
OBJECTIVE: Development of new technologies and policy trends require the concepts of prime land and marginal land to be renewed from time to time. Although much research has been done on the concept of marginal land, it is currently limited by the lack of a clear, globally accepted definition.
METHOD: There are four major sources of criteria of marginal lands: economic (e.g., rent cost, land value), geographical (e.g., temperature, slope, precipitation), ecosystem-based (e.g., protected areas, recreation, ecosystem services), soil suitability (e.g., yield capability, physical and chemical soil properties). The categorisation of agricultural land into groups like productive, marginal or unproductive often depends on the cultivation or management type.
RESULTS AND CONCLUSION: Since conceptions of marginal land are dynamic both in time and space, flexible policy and practical solutions are needed for their non-degrading use, which in any case shall support nature-based socioeconomic development. To maintain the socioeconomic value of these areas, it is crucial to develop rural areas that are economically or biophysically marginalised. High nature value farming, bioenergy crops by sustainable land management and afforestation are highly recommended. Choosing the right management can transform marginal land into an optimal soil condition or incorrect management can degrade prime land into marginal land (unproductive land).
SIGNIFICANCE: This paper provides a review and categorisation of the historical and new developments of marginal land concepts especially those which are working with agricultural aspects, including land management and reclamation. It could give a strong basis for further research in topic of marginal land.

* Corresponding author.
E-mail address: csikos.nandor@atk.hu (N. Csikós).

https://doi.org/10.1016/j.agsy.2022.103560
Received 14 June 2022; Received in revised form 9 September 2022; Accepted 9 November 2022
Available online 16 November 2022

1. Introduction

Extension of agricultural lands to marginal areas to improve food security and farmers' income, to support bioenergy production and provision of raw materials has gotten a lot of attention around the world. Agriculture covers about 38% of the Earth's land surface, divided into 1.5 billion hectares of cropland and 3.4 billion hectares of pastures (Alexandratos and Bruinsma, 2012). To meet projected food demand in 2050, an additional 0.2 to 1 billion ha of agricultural land may be required (Tilman et al., 2011). In the same time, there is widespread agreement that human expansion of agricultural land should be limited. Based on the IIASA and FAO in the Global Agro-ecological Zones V3 studies (IIASA/FAO, 2012) there is a large quantity of land suitable for agriculture with varying degrees of productivity. Marginal land class (marginally suitable, very marginally suitable) cover 2.7 billion ha worldwide from which 1.5 billion ha is unused land which are suitable for agricultural cultivation, but currently not cultivated. At the same time, much of the areas currently considered as marginal could sort out from this category if used more efficiently.

Defining marginal land is a complex task, which may not be limited to the biophysical quality of the land. The term of marginal land shows up in the early 19th century in the Theory of Rent from Ricardo, D. (Ricardo, 1817). Complex scientific investigation of lands' low productivity has been started in the 19th century. Peterson and Galbraith, 1932 began to develop a new theory of marginal land types in detail in the context of a new, modern land use planning concept. Since the early times of the appearance of marginal land theories, categories like 'physical marginal land', 'production marginal land', and 'economic marginal land' were all used in different contexts and with different concerns. Due to the growing population and weather extremes caused by climate change, more conscious and sustainable land use planning has become even more important in recent decades, which require the concepts of prime land and marginal land to be renewed from time to time (Kang et al., 2013). The definitions of marginal land and its application domains differ across regions, countries, and organizations due to their different objectives (Baldock et al., 1996; Dale et al., 2010; Esch et al., 2018; FAO, 2008, 1993; Gopalakrishnan et al., 2011; Tang et al., 2010; Wells et al., 2018). The same attributes that make a site "marginal" in one place or for one purpose might make land productive in another place or for a different reason (Dale et al., 2010; James, 2010). Physical and production marginality of lands are commonly used by soil scientists. Criteria affecting yield, such as soil conditions including sodicity, salinity, water management and physical characteristics are becoming primary indicators of marginality. Some of the affected areas are not only low in productivity, but also have limits that prevent them from being used for traditional agricultural operations (Hart, 2001; Jones et al., 2014; Schubert et al., 2008). These lands can be classified as Less Favoured Areas, which can be translated as marginal land (Confalonieri et al., 2014; Jones et al., 2014) further to productivity.

Soil-based ecosystem services play a vital role in multiple aspects of land quality; they can protect the land from erosion and organic matter loss, as well as balance soil variables, and their loss presents a significant risk (Baude et al., 2019). Most of the researches investigate marginal lands from the viewpoint of agricultural - or just arable - land use. However, forest and grassland are land use types which very often take place on marginal lands and in many cases, they could be used as croplands. Marginal lands (pastures) can be used for diary production and it must be used to save prime land for crop production (Van Kernebeek et al., 2016). Grazing with livestock actively helping to store carbon and to maximise use of marginal land and resources too (Garnett, 2009). Important to note that, due to environmental and mostly human impact, a prime land can be degraded to marginal land or unproductive land, but the marginal lands (or some cases unproductive lands) can be turned into productive land by appropriate land management or targeted amelioration (Kang et al., 2013; WOCAT, 2022) (Fig. 1). The categorisation of lands into prime land, marginal land or unproductive land is often depends just on the management or cultivation type of the land. Land evaluation is a key tool to categorise that. Development of land evaluation systems based on biophysical conditions have been started in the 20th century (Bouma, 1989; Burrough, 1989; Doran et al., 2018; Karlen et al., 1997; Karmanov and Friyev, 1985; Klingebiel and Montgomery, 1961; Kreybig, 1935; Kumar et al., 1984; Makhdoum, 1993; Máté, 1960; Shao, 1984; Sigmond, 1935; Sisov et al., 1991; Storie, 1976).

It is still an open question if there is any difference between marginal lands and production area with special needs or these two terms mean the same.

The aim of this study is to provide a comprehensive review of the historical and new developments of agricultural marginal land concepts, including land quality assessment aspects and related indicators, management and evaluation of marginal land types from the viewpoint of agricultural use. We also aimed at establishing criteria systems based on the relevant variables to separate and classify these areas. The motivation of this manuscript was to help to navigate between historical and new concepts and managements options of agricultural marginal lands, and to help researchers choose from existing concepts for their own specific purpose - or create new ones.

2. Marginal land concept approaches

Defining marginal land is a complex task, with a need to consider a series of land quality criteria. To understand the full process of marginal land evaluation, first, we have to understand basic concepts of land quality and processes of land evaluation. According to the work of Rossiter (1996) the meaning of land quality is "a complex attribute of land which acts in a manner distinct from the actions of other land qualities in its influence on the suitability of land for a specified kind of use; the ability of the land to fulfil specific requirements for a land utilization type" and the definition of land evaluation is "The process of predicting the use potential of land on the basis of its attributes. It does not include optimal land allocation. However, land evaluation supplies the technical coefficients necessary for optimal land allocation" (Rossiter, 1996). We took these definitions, with a focus on agricultural land as a guidance for our review.

2.1. Historical background of marginal land concepts and evolvement of land evaluation

The term of marginal land is not a new terminus technicus. It shows up in the early 19th century in the Theory of Rent from Ricardo, D. (Ricardo, 1817). He made four categories, first two categories called

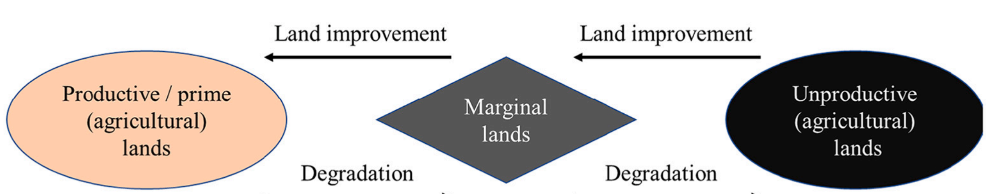


Fig. 1. Transformation scheme of agricultural lands between prime land and unproductive land.

intra-marginal land, the third one called as marginal or no rent land and the fourth category was the below-marginal, which is not suitable for cultivation. Hollander also approached the issue of marginal land from an economic point of view (rent payment) (Hollander, 1895). The investigation of lands' low productivity based on other variables than economic, like soil and climate parameters, has been started around the beginning of the 20th century and it started to be linked to the marginal land concept. Peterson and Galbraith (1932) began to develop the theory of marginal land types in more detail within the context of a new land use planning concept which gives the possibility of a more rational use of land resources in the USA. They use major and minor factors which were the foundation of a new remuneration system, 'grade of land' (Peterson and Galbraith, 1932). They also mention that for a more appropriate marginal land definition and land use plan, the planners should consider the climate, fertility of soils and also the growing population. According to their proposal, physical marginal lands, production marginal lands, and economic marginal lands shall all be used in different contexts and with different concerns.

Modern land evaluation practice grew out of agricultural land capability classification by working groups of soil scientists and agronomists in the second half of the 20th century (Fig. 2). A working group of the Food and Agriculture Organization of the United Nations (FAO)'s proposed a milestone methodology published as the "Framework for Land Evaluation" in 1976 (FAO, 1976). The FAO organized further activities which resulted in the publication of guidelines for land evaluation in dryland agriculture (FAO, 1983), irrigated agriculture (FAO, 1985) and also for sustainable land management (FAO, 1993).

Soil quality assessment is one of the key components of the land evaluation systems. Bünemann et al. (2018) in their comprehensive review characterised soil quality concepts as having a continuous change. Before 1970 the aim of soil quality assessment was either the identification of suitability for crop growth or estimation of productivity. Between 1970 and 1990 estimation of productivity levels remain the main objective for which soil quality indicators have been used. Between 1990 and 2010 measures used soil quality test kits, biochemistry analysis and multivariate statistics to establish productivity, environment degradation and animal/human health indices. From 2010 the main objectives were the multi-functionality, ecosystem services, resistance and resilience analysis with high-throughput methods. Land evaluation methods can be qualitative, quantitative or a combination of the two in terms of land fertility (Bouma, 1989). Quantitative, qualitative and hybrid land evaluation systems can be static or dynamic (Van Lanen et al., 1992). Descriptive, qualitative systems usually provide quick but general answers about productivity potential. They can be used for simple characterization of growing conditions, but also require the inclusion of quantitative criteria for detailed description. Qualitative systems group land based on specific land-use objectives and taking into account constraints (Dumanski and Onofrei, 1989; Sanchez et al., 1982). According to Burrough (1989), land evaluation models can be divided into three groups: empirical models, deterministic models and stochastic models. Few example, like regression models, which process data from experimental observations using univariate or multivariate regression analysis (Godev and Klestov, 1971; Trashliev et al., 1971). Threshold models use the extreme values of diagnostic properties to determine output values (Johnson et al., 1994). Deterministic models (or deterministic process models) are based on well-known physical and chemical processes and their underlying physical rules. Factors and their weights determining soil quality are obtained from the results of differential calculations describing the processes. If an "average" behaviour can be described by a well-defined stochastic process, then the output of the model is a parameter that describes the whole process with a feasible value (Bouma and van Lanen, 1987). Relying on the theory of qualitative classification, it groups soils according to the similarity of limiting factors or constraints, the approach taken by many Western land evaluation systems (Klingebiel and Montgomery, 1961; Sanchez et al., 1982; Sys, 1985). These factors can be either barriers to water and nutrient access for plants or obstacles to cultivating the land. The main factors that limit crop production are insufficient climate, shallow topsoil, poor water management, over-watering, high salinity, erosion, steep slopes (Da La Rosa and Magaldi, 1982; Haans and Heide, 1984; Klingebiel and Montgomery, 1961; Magaldi and Ronchetti, 1984). With the assessment of these constraints and their weight in the success of agricultural production, marginal land can be distinguished from prime land.

Quantitative land evaluation systems, which are based on biophysical properties do not simply classify soils according to their suitability for crop production, but also describe the level of fertility, with a relative value. Examples of these systems include the most of the Eastern European soil evaluation systems (Fórizsné et al., 1972; Dzatko, 1995; Karmanov and Friyev, 1985; Sisov et al., 1991) Storie index (Koreleski, 1988; Storie, 1976), and the Productivity rating index (USDA, 1951) of the USA. Soil fertility classifications combining both qualitative and quantitative systems (Hu et al., 1999; Riquier et al., 1970; Sys, 1985; Van Lanen et al., 1992) can be beneficial in supporting complex land use tasks. While descriptive (qualitative) models aim at estimating the suitability for land use and quantitativemodels at classifying the fertility of the land, the combination of the two models provides a means of that also takes into account the factors that play a role in achieving a given yield level.

2.2. Current concepts of marginal land

In the last decades, conscious and sustainable land use planning has become even more important due to the growing population and the weather extremes caused by climate change. In the meantime new technologies bring new innovations that require the concepts of prime land and marginal land to be renewed from time to time (Kang et al., 2013). In the last 30 years the term "marginal land" is frequently used interchangeably with other terms such as "unproductive lands," "waste lands," "underutilized lands," "idle lands," "abandoned lands," or "degraded lands" (Dauber et al., 2012; FAO, 1976; Lal, 1991; Tógyer, 2012; Wiegmann et al., 2008) (Fig. 3).

The definitions of marginal land and its application domains differ across regions, countries, and organizations due to the different management objectives of the areas of concern (Baldock et al., 1996; Dale et al., 2010; Esch et al., 2018; FAO, 1993, 2008; Gopalakrishnan et al., 2011; Schroers, 2006; Tang et al., 2010; Wells et al., 2018). Shortall

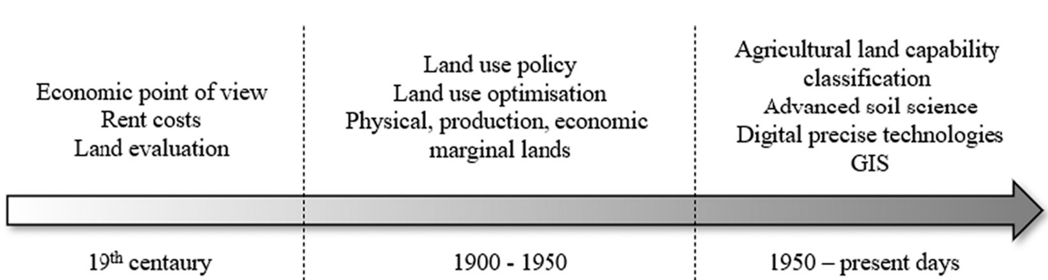


Fig. 2. Main drivers and characteristics of the changing marginal land conceptions during 19th and 20th centuries.

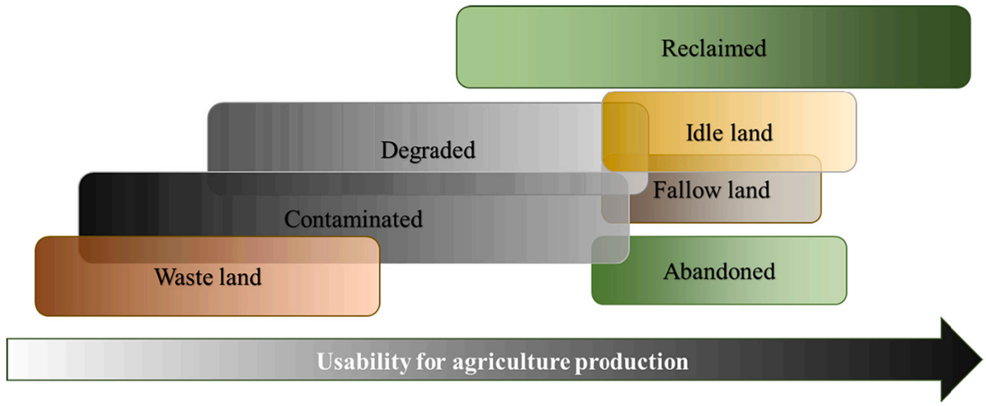


Fig. 3. Agricultural marginal land types in relation to agricultural usability.

(2013) differentiate three kinds of marginal land: land not fit for food production, ambiguous lower quality land and economically marginal land. Dauber et al. (2012) calls it surplus land which are suitable for bioenergy production and investigate this topic from a socio-economic and ecosystem services point of view. It is critical to understand which bioenergy production techniques are best for the various types of surplus land, taking into account factors like yields, inputs, and costs, as well as potential environmental and socio-economic consequences. Wiegmann et al. (2008) name the marginal land as degraded land, which are not cultivated currently. Based on their work, the most important is to identify the degraded lands and analyze possibility of bioenergy use or conservation for natural habitats. Based on the work of Khanna et al. (2021) marginal land definition for bioenergy is likely to encompass land that is biophysically poor and land that is currently idle/fallow (economically marginal land for food crops), as well as land that is in crop production but losing soil organic matter, suffering from erosion or high nutrient run-off, or foregoing significant habitat value (socially marginal land for food crops) (Khanna et al., 2021). According to Schroers (2006) marginal land is an area where cost effective production is not possible because of factors like soil quality or land use policies. According to Dale et al. (2010) marginal land is a relative term which can vary by countries, organization and land use purpose. Land is economically marginal if the combination of yields and prices barely cover the cost of production. It is also important to carefully examine ecosystem services and cultural values during land use planning. Esch et al. (2021, 2018) analysed the suitability of marginal lands for crop production in Canada. Marginal lands can be used as an important starting point for assessing geographically explicit suitability for crop production. As James (2010) stated, marginal land is thought to be land that isn't being used for current production needs or is of such poor quality that it is unsuitable for modern intensive cropping systems. Such lands have the potential to produce biomass without displacing traditional crops. According to the study of James (2010), biomass grown on marginal lands has the potential to be carbon neutral or even negative. However, using degraded or marginal lands for biomass production is unlikely to be as effective at reducing carbon emissions as simply reforesting or reseeding the land and managing it as native cover (Fargione et al., 2008).

With the development of modern geoinformatics systems and ever-evolving earth observation systems, land assessment models have also evolved considerably and many studies have been carried out involving different land variables (Gopalakrishnan et al., 2011; James, 2010; Tógyer, 2012; Tóth et al., 2021). Although remote sensing is useful for identifying low-productivity land based on lands' biophysical characteristics. Since economic marginality requires a much more flexible and dynamic characterization of all the social and economic factors that motivate the rural policymakers to allocate their land to specific use. Marginal lands can be used for diary production and it must be used to save prime land for crop production (Van Kernebeek et al., 2016). Grazing with livestock actively helping to store carbon and to maximise use of marginal land and resources (Garnett, 2009). Bioenergy can have a double impact on marginal land, energy production and feed for livestock (Helliwell, 2018; Mooney et al., 2015; Muscat et al., 2022).

Marginal lands have been defined, on the one hand, in Europe as land uses that are on the margin of economic viability (Strijker, 2005). The "margin of economic viability" is a relative term; the same characteristics that make a site "marginal" in one location or for one purpose can make land productive in another location or for a different purpose (Dale et al., 2010; James, 2010).

On the other hand, soil scientists frequently use physical marginality and production marginality of lands based on soil suitability and other limitations of land use. Marginal lands are areas that are not only low in production but also have constraints that make them unsuitable for agricultural practices (Hart, 2001; Jones et al., 2014; Schubert et al., 2008). Wissenschaftlichen Beirats der Bundesregierung Globale Umweltveränderungen (WBGU) (Schubert et al., 2008) defines marginal lands as areas with low agricultural or forestry productivity, such as arid and semi-arid grasslands, desert fringes, and areas with steep ground and structurally weak or erosion prone soils, especially in mountainous regions. Alternatively, marginal land also covers formerly productive areas that have lost their yield potential due to human-induced soil degradation (e.g., overused, degraded, and thus unproductive land, including both forests, pasture and arable land), or have been intentionally taken out of production.

In China the use of prime land to produce bioenergy is not allowed, therefore wasteland and paddy lands (natural grassland, sparse forest-land, scrubland and unused land), which are described as marginal lands are used to grow energy crops (Zhang et al., 2012).

According to the Asia-Pacific Economic Cooperation Energy Working group (APECE-WG, Milbrandt and Overend, 2008), the marginal lands have a harsh climate, poor physical characteristics, and are difficult to cultivate. Such areas can also be characterised with insufficient rainfall, extreme temperatures, poor soil quality, steep terrain, or other agricultural limitation issues.

According to the USDA-NRCS, prime farmland is defined by the optimal combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops (USDA-NRCS, 2010). Marginal lands are the reverse of prime farmland, and are limited by inherent soil characteristics. The EU Common Agricultural Policy for the period 2014–2020 required the identification of areas which facing natural constraints. These areas called Less Favoured Areas and it can be interpreted as marginal land (Confalonieri et al., 2014; Jones et al., 2014). Table 1 shows the summary of the definitions and descriptions of marginal lands.

The high sensitivity of marginal lands' ecological services has become a major source of concern (Baldock et al., 1996; Dale et al.,

Table 1
Marginal land concepts and their main attributes.

Category	Variable	References	Description
Economic	Rent fee	Ricardo (1817)	Established four categories: intra-marginal, marginal and below-marginal
Economic	Rent payment	Hollander (1895)	Define marginal lands up to Ricardian below-marginal definition
Economic	Standard of living, farm size, price of crop, cost of cultivation	Peterson and Galbraith (1932)	Define 'grade of land' based on multiple variables, static (standard of living, farm size) and dynamic factors (price of crop, pecuniary cost of cultivation)
Biophysical, Ecosystem services	Bioenergy plant type, biodiversity, landscape	Dauber et al. (2012)	Land currently not in use for the production of food, animal feed, fiber or other renewable resources due to poor soil fertility or abiotic stress, and land currently no longer needed for food and feed production
Biophysical	abandoned farmland, unused degraded land	Wiegmann et al. (2008)	Land degradation is the decline of natural land resource. Global identification of degraded land needed. Marginal land is an economic or a suitability term.
Biophysical, Ecosystem services, Economic	economic, environmental attributes, original land use	Dale et al. (2010)	Classify a site as being "marginal" in one place or for one purpose can result in land being considered productive in another place or for a different purpose.
Biophysical	Soil fertility, yield, land use	Schroers (2006)	Marginal land is an area where cost-effective production is not possible under given side conditions (e.g., soil productivity), cultivation techniques, agriculture policies, as well as macroeconomic and legal conditions
Biophysical	Soil fertility, yield	Esch et al. (2021)	Marginal lands are defined as being severely limited by texture, drainage, fertility, slope or climate
Biophysical, Economic	soil health, profitability, environmental degradation	Gopalakrishnan et al. (2011)	Based on soil health criteria: eroded, slope (>15), corn yield (< 9 t/ha), frequently flooded; land use: marginal agricultural land, near riparian or roadway; environmental degradation: nitrate contaminated, brownfield, irrigated cropland, impaired streams.
Economic	Socio-economic factors	Strijker (2005)	Marginal lands are defined by land uses that are on the edge of economic viability; however, they are not always associated with low input use.
Biophysical	Soil fertility, geographical factors	Hart (2001)	Marginal land are soils with low inherent fertility and topography unsuited to modern farm machinery.
Biophysical, Economic	Soil fertility, human impact, economy	Schubert et al., 2008	Areas with little capacity for fulfilling a production or regulation function, and also for areas that have lost their production and regulation function, sometimes to a significant extent
Biophysical	Soil, environmental attributes	Jones et al. (2014)	Less Favoured Areas (LFA) are defined as rural areas where farming conditions are more difficult due to natural constraints, which raise production costs and limit agricultural opportunities.
Biophysical	land cover, soil, climate	Milbrandt and Overend (2008)	Marginal lands are characterised by poor climate, poor physical characteristics, or difficult cultivation. They include areas with limited rainfall, extreme temperatures, low quality soil, steep terrain, or other problems for agriculture.
Biophysical, Economic	land use	Zhang et al. (2012)	China defines marginal land that may be used for growing energy crops as wasteland and paddy land fallowed in winter. Wasteland includes natural grassland, sparse forestland, scrubland and unused land that may be used to grow energy crops.
Biophysical	soil fertility, environmental attributes	Liu et al. (2013)	Marginal land is defined by specific physical criteria and includes unused land as cultivable potential land sources as well as land that is marginally located and not usually used for food crops due to its small size or unclear ownership.

2010; Wood et al., 2000). The inadequate use of marginal land can have many negative consequences, such as wind erosion, nitrate enrichment in groundwater, loss of biodiversity (flora, fauna), soil structure degradation, etc. (Bertzky et al., 2011; Bindraban et al., 2009; Csikos et al., 2019; Duttmann et al., 2014; Immerzeel et al., 2014; Plieninger and Gaertner, 2011). Sustainable management of ecosystem services may help to mitigate soil degradation while also increasing the production of services for both private landowners and society (Breure et al., 2012).

We prepared a word cloud based on the assessemnt of scientific literature which gives the possibility to analyze identify the most used topic in case of current days' marginal land researches. Fig. 4. shows the most frequently used terms in the 'marginal land' topic in the first 100 articles from the Google Scholar database (http://worldcloudit.com). The first five terms are biomass, crops, species, breeding, mals, traits, yield, production, genetic and quality. Based on these terms we can state that todays researchers mostly interested in the production of biomass on marginal land, but there is also a strong focus on management and the special characteristics of these lands. In general, these studies are based on the economic and environmental characteristics of the land.

(http://worldcloudit.com)

3. Factors influencing and indicators characterising marginal lands

As presented in the previous chapter, many researchers and authors have defined the term marginal land over the last 200 years. Many authors have only defined this phrase in general terms while others have linked the delimitation of these lands to specific parameters. There are several types of these parameters, and some researcher use only economic, some use only biophysical and some use both.

Klingebiel and Montgomery (1961) grouped agricultural lands into categories and classes based on their biophysical attributes and characteristics. As subclasses they determinate four type of limitations and hazards: erosion hazard, wetness, rooting zone limitation and climate. They established eight further classes and class I to class VIII the risk of soil limitation became greater. Classes 1 to 4 are also classified according to the crops, and indicate soils that are suitable for the cultivation of domesticated crops. Soils in classes 5 to 7 are only suitable for the cultivation of adapted indigenous plant species, while the lowest class, class 8, is not suitable for agricultural production.

One of the advantages of the above classification, in addition to assessing the suitability of the land for crop production, is the ability to classify the land according to its management functions and potential, which can be used to decide on the final use of the land in the context of the available agrotechnology/technology.

Karmanov and Friyev (1985) use the so-called Soil Ecological Index (SEI) to express the soil productivity potential. The methodology was adopted by Sisov et al. (1991) with the indices corrected according to crop requirements, with different rates for different soil types and climatic conditions, to calculate the productivity value. The following equation is used to calculate the SEI:

$$SEI = 12.5(2-\delta) \times V \times O \times \frac{\Sigma t^{o} > 10^{o}(MI-c)}{CC+100} \times AC$$

where δ - the bulk density, V - the "useful soil volume" (a ratio including the weighted importance of the different mechanical composition per

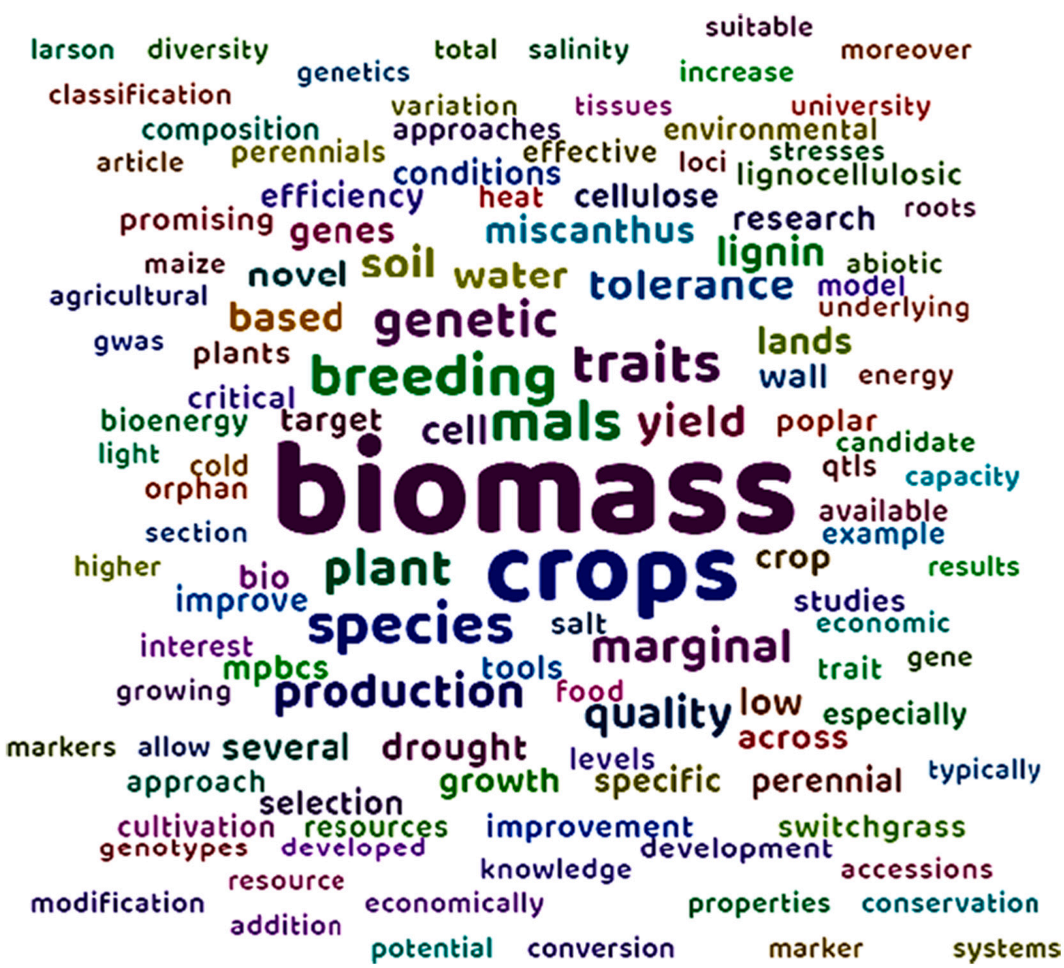


Fig. 4. Word cloud of 'marginal land' based on websites of google search results.

soil type), O - other characteristics (according to limitation), $\Sigma t^o > 10^\circ$ - cumulative annual mean temperature, taking into account days with daily mean temperatures above 10 °C, MI - moisture index, c - correction coefficient for the moisture index, CC - continentality coefficient (according to latitude), AC - aggregated agrochemical characteristics, 12.5 – standard value.

The first more complex, multi factor-based land evaluation concept coming from the FAO (1993) work, 'An international framework for evaluating sustainable land management'. This framework uses biophysical factors to classify a land into groups. Marginally suitable groups are based on the followings: growing period <210 days, Evapotranspiration >0.55 1-ETa/ETm, soil drainage poor, water table depth < 50 cm, pH < 4 or > 8, CEC 0–20 cm < 6 meq%, base saturation < 20%, EC of saturation extract >9.

Gopalakrishnan et al. (2011) identified marginal land resources based on soil health, land use and environmental degradation in Nebraska (USA). Based on the biophysical attributes of the land the marginal land is eroded, frequently flooded (> 50%), poorly drained (classes 6 and 7), highly sloped (> 15°) and low productivity for the main grain crop (nonirrigated yields of corn <9 tones/ha). Land can be marginal if land use includes idle and fallow cropland or conservation reserve program land. Volume of land degradation, like brownfield sites contaminated with chemicals or surface water/groundwater are contaminated or irrigation can lead to depletion of water resources. Land is also marginal when the nitrate level of groundwater exceeds 10 mg/L.

Milbrandt and Overend (2008) in the Energy Working Group of APEC declared marginal lands based on biophysical parameters including bare or herbaceous areas, moderate (8–16%) and steep slope (16–30%), shallow soil (<50 cm), poorly drained soils, low or moderate natural fertility, coarse or sandy soil, soils with heavy cracking clays (vertisols and vertic sub-groups), salt-affected soils (Solonchaks, Solonetz, and Solodic Planosols), Soils with gypsic horizon, acid soils (pH <5.5), soils with high calcium level or peat soils.

Cai et al. (2011) published a paper on world-wide land availability for biofuel production based on low resolution global datasets. The aim of this research was to identify marginal land too by remotely sensed data: 1 km Harmonized World Soil Database, 1 km Global Terrain Slope, 2.5 km soil temperature regime (USDA-NRCS), 2 arc-degree monthly temperature and precipitation mean (Climatic Research Unit) and 1 km land cover (IGBP).

The European Union's Joint Research Centre combined several biophysical criteria to delineate those agricultural areas which are affected by specific constraints (Jones et al., 2014). Criteria are the followings: growing period days ≤180, thermal time ≤ 1500°-days, dryness P/PET ≤0.5, soil moisture excess days more then 230, wet within 80 cm (6 moths) or 40 cm (11 months), coarse material ≥15% or half or more in 100 cm is sand or loamy sand or heavy clay (≥60%) or organic soil in 40 cm or top soil contains ≥30% clay, rooting depth ≤ 30 cm, salinity ≥4 dS/m or sodicity ≥6 ESP in 100 cm or pH ≤ 5 (topsoil water). Slope of the land is bigger than 15%. Another criteria set from the Joint Research Centre contains sub-severe thresholds proposed by the expert (Confalonieri et al., 2014).

Yang et al. (2020) did country scale (USA) analysis to delineate marginal land for bioenergy crop production based on remote sensed data. They used the following datasets to their modelling: 10 m soil (gSSURGO), 1000 m slope model (GTS), 1000 m temperature & precipitation, 32 km evapotranspiration data, 30 m National land cover, 30 m Cropland Data Layer, 250 m Irrigation (MIrAD-US), 250 m Gross Primary Productivity (MODIS), county/state wide crop yield (NASS surveys) and region wide crop production cost.

Tógyer (2012) shows the Hungarian Agricultural Research Institute's yield-base method, which is an economic point of view calculation. Market value of the land is related to yield (kg wheat) calculated from the multiplication of the annual income of land, yield (kg wheat) calculated from the multiplication of rent considered characteristic of the immediate surroundings of the land, the average domestic stock market price of wheat (HUF/kg), capitalization rate (%/100), the correction factor (%/100) used to modify the calculated market value of the land within consolidated criteria.

Esch et al. (2021) have done a complex delineation of economically marginal land in Canada, and took into account several types of factors including historical and present economic and population data using a SWOT analysis. They used historical farm operating expenses; the amount of fertiliser used. They also employed market prices: farm product and crop prices; government subsidies and profits; rental payments.

According to the review of Bünemann et al. (2018), 40% of research articles (62 publications) use the following indicators (in descending order): total organic matter/carbon, pH, available P, water storage, bulk density, texture, available K and total N. Bünemann et al. (2018) also collected several novel indicators from the last decade like fungal:bacteria ratio, abundance of individual soil organism (presence richness), faunal community indices (maturity, enrichment, channel index), Metabolic quotient (qCO2), microbial quotient (MicrC/SoilC), potentially mineralizable nitrogen, soil respiration, nitrogen mineralization, denitrification and Fingerprinting methods (e.g., DGEE, T-RFLP, A-RISA, ARDRA, TGGE).

Based on our current literature review, we propose a scheme of indicators of marginal land, including soil factors, other environmental factors and economic factors (Fig. 5).

4. Guiding principles and best practices for the use of marginal land

Principles of sustainable land management, including profitability and land conservation apply also to marginal lands which are between the prime lands (best for food production) and unproductive lands (unsuitable for agricultural production). However, marginal lands need distinctive site-specific management based on the knowledge of the limiting factors, their combined effects and (i) available practices to overcome the limitations and (ii) specific cultivars which tolerate the unfavourable conditions. Because of generally low productivity and thus profitability is expected on marginal areas, financial and policy instruments are often needed for successful farming. According to the review of Muscat et al. (2022) main policies and related projects targeting marginal lands in the European Union can be framed to three major areas: sustainable bioenergy, rural development and ecosystem restoration.

Among these domains most of the scientific articles in the last decade (according to http://webofknowledge.com) target the aspects of bioenergy production on marginal lands. The idea behind sustainable bioenergy production on marginal lands is that shifting bioenergy to these areas is one of the key solutions to address sustainability issues in a wider spatial context, including competition with food production and direct and indirect land-use change (Muscat et al., 2022). Industrial crops can be used to produce high-value-added products and bioenergy. This approach has the potential to strengthen the growing bio-based industry, reduce competition in land use, increase farmer incomes, and increase the value of marginal land (Elbersen et al., 2017). Lands concerned for bioenergy purposes are usually abandoned land, degraded land, contaminated land, land with economic and biophysical constraints. The list of incentives to bring marginal lands to cultivation for bioenergy include income support, and tradable carbon certificates based on environmental assessment. A thorough investigation always necessary before bioenergy plantation, because non-appropriate procedures can lead to many negative consequences like increased soil erosion and compaction risks (Duttmann et al., 2014), increased nitrogen mineralization and leaching risks (Claus et al., 2014; Svoboda et al., 2013), and changes in local bio-diversity (Brandt and Glemnitz, 2014; Csikós and Szilassi, 2020). There are big differences between the crops, e.g. the switchgrass (as other perennial crops), which can stabilized the

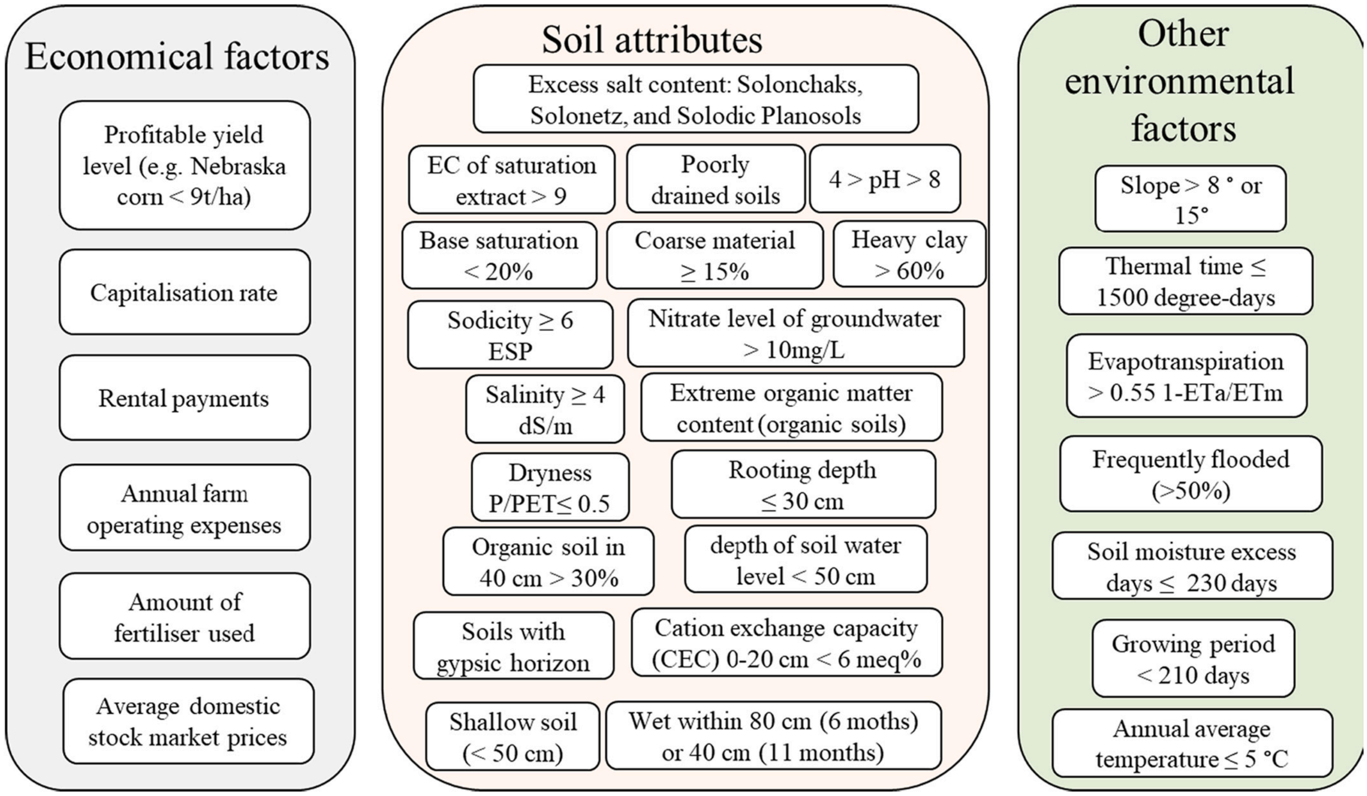


Fig. 5. Most frequently used economic, soil and other environmental indicators in marginal land assessments.

carbon dynamics and increase the humification, unlike silage maize, which leads to the opposite processes (Zhu et al., 2018). The MAGIC (Marginal Lands for Growing Industrial Crops) project (MAGIC, 2022) had collected and rated the yield ratio of 37 industrial crop under different soil conditions, creating a rich database for choosing crop type according to the marginal land type. For example, MAGIC project researchers found that Camelina could be a good alternative crop of many marginal lands in Europe. It has a wide range of environmental adaptability, low input requirements, pest and disease resistance, and multiple applications in food, feed, and biobased products and improve the biodiversity and soil characteristic (Zanetti et al., 2021).

Land is being abandoned in Europe, resulting in rural disintegration, as well as the loss of traditional farming methods, farm livelihoods, and tourism. Development of the rural areas, which are economically or biophysically marginalised is very important to preserve the socio-economic value of these areas. Another issue is that there are few opportunities for farmers to make a living on marginal land (Benayas et al., 2007). On the other hand, marginal land is seen as a way to preserve traditional farming methods and rural landscapes. Direct income support for farmers in marginal land areas, as well as assistance in helping farmers adapt to marginal conditions, such as through the use of appropriate livestock breeds, are the primary solutions (Ruskule et al., 2013). High nature value farming, bioenergy crops and afforestation (bio-based material applications) in marginal land are highly recommended (Muscat et al., 2022). In Latvia, Abolina and Luzadis (2015) made experiments in abandoned lands with short rotation woody crop cultivation. The aims are to encourage land management, to increase the support of small farm holders and young farmers, to enhance the environmental and biophysical characteristics of these lands and to reduce social marginalisation in rural areas. A main element of the utilisation of marginal areas is livestock breeding, which may have significant environmental impact. Nevertheless large areas of land have been used to feed livestock (Mottet et al., 2017), mostly used for grazing or feed production. As in traditional land use systems, grassland that cannot be used as arable land should use for grazing which is the most effective practice on this land use type (Petersen and Snapp, 2015). Bioenergy related feedstocks (e.g. corn stover, switchgrass) could be valuable supply for farms to feed livestock, so the bioenergy has a double effect in rural development in marginal lands (Helliwell, 2018; Mooney et al., 2015; Muscat et al., 2022).

Restoration of the ecosystem is an important task in marginal land areas. Marginal lands which are almost unproductive or highly degraded can be turn into productive land again. Marginality is not a permanent state of the land, just a state in between prime land and unproductive land (Fig. 1). Klingebiel and Montgomery (1961) collected 8 indicators to put soils into capability classes (Table 2).

These indicators represent biophysical properties which can negatively affect lands and make them marginal lands. Any unfavourable recurring or permanent soil or landscape features may limit the land's safe and productive use. One disadvantageous feature of the soil may make it unusable, necessitating extensive, ameliorating treatment. Several minor undesirable characteristics combined may become a major issue, limiting the use of the soil.

The World Overview of Conservation Approaches and Technologies for Sustainable Land Management has several best practice examples for ecosystem restoration in marginal land area. For example, in Thailand the use of bio-fermentation for the production of organic soil amendments as an alternative technology is a successful practice that helps to restore land degraded by intensive use and restore the fertility level. WOCAT also introduces several projects in Afghanistan, for example a plan for rotational grazing, which has been developed to control pasture use and prevent overgrazing of rehabilitated pastures. In another project degraded pastures are restored with alfalfa through broad seeding method. The area is put under quarantine for three years to allow for the pasture to restore sufficiently. In mountainous areas micro irrigation canal system was established for supplying water to poplar plantations on sloping lands and non-fruit and fruit trees are planted on heavily degraded forest land to protect the land from erosion and further

Table 2
Main limitations and hazards of soils and lands and their mitigation solutions.

Limitation*	Solution
Soil attributes	
Base saturation	The lime treatment increased soil exchangeable Ca2+, the alkaline slag treatment increased exchangeable Ca2+ and Mg2+ levels, and the biochars (peanut and canola) and combined applications of alkaline slag with biochars increased soil exchangeable Ca2+, Mg2+ and K+ and soil available P (Masud et al., 2014).
Cation exchange capacity	Increase the five most abundant exchangeable cations in the soil, calcium (Ca++), magnesium (Mg++), potassium (K+), sodium (Na+) and aluminium (Al+++) (Domingues et al., 2020).
Kind of clay mineral	As evaluated by aggregate stability and clay dispersion, amorphous and crystalline aluminium and iron oxide minerals play a vital role in stabilizing soil structure. Clay minerals are stabilized by aluminium and iron oxides, which reduce critical coagulation concentrations, clay dispersion, water uptake, and clay swelling while also promoting microaggregation (Goldberg, 2008).
Organic matter	Increasing of soil carbon with management-intensive grazing practices show that the farms accumulated C at 8.0 Mg ha − 1 yr − 1, increasing cation exchange and water holding capacity by 95% and 34% (MacHmuller et al., 2015).
Water holding capacity	Composted leaf litter, termite mound material, and bentonite treatment can increase the organic matter and the water holding capacity (Suzuki et al., 2007).
Texture and structure of rooting zone **Rooting depth**	Combination of subtle soil disturbance to a depth of approximately 300 mm using a specially designed blade loosener, with controlled traffic and no-tillage can improve the rooting and the yield (Hamilton et al., 2016). Rotational planting of deep-rooted crops will help to avoid or alleviate compaction, enhancing root distribution and rooting depth (Unger and Kaspar, 1994).
Erosion	Agricultural areas continuous plant coverage can prevent the soil from erosion (Guerra et al., 2016; Zuazo and Pleguezuelo, 2009). Sloped areas with intensive rainfall can be protected by terraces with high coverage grassland at lower dike terraces (Liu et al., 2013).
Continuous or periodic water logging	
Slow permeability High water table Flooding	Drainage of water, prevention of further flooding by dams or land filling, improvement of soil structure with organic matter.
Saline-sodic	Remove soluble salts or exchangeable sodium
Physical obstacles	Removing stones and fill deep gullies
Climate (Temperature and moisture)	Cultivating crops that tolerate low temperature and short growing season (mostly in north) Irrigation of semiarid and arid areas

* List of limitations and suggested solutions are based on Klingebiel and Montgomery (1961) if not indicated otherwise.

degradation and provide fuelwood for the local community. They also cultivated the slopes with Ferula to protect cropland and grazing land from erosion. In Bangladesh the strip tillage wheat cultivation is a climate-smart technology to save water and improve soil health. In Botswana split ranch grazing method involves grazing half the available area for a full year - concentrating livestock and the consequent grazing pressure maintains the grassland in an immature, high-quality state. Grazing with livestock actively helping to store carbon and to maximise use of marginal land and resources (Garnett, 2009).

5. Conclusion

Approaches to identify and classify marginal lands are manyfold, largely depending on the spatial scale of the assessment and the regional conditions for which the assessment is carried on. As an area to be classified may be suitable for one utilisation while unsuitable for another, the identification of marginal areas shall be purpose specific. Identification of the marginal land type (biophysical, economic or ecosystem service) is essential for the planning and implementation of site-specific management. For example the marginal land is suitable for bioenergy or it needs rural development or ecosystem restoration. Furthermore, marginalisation is a process in time, which is sometime irreversible, while in other cases with the amelioration a previously marginal land can be turned suitable for the objective of the use. Taking all the above considerations into account, concepts of marginal land and methods of identifications usually follow two distinct approaches for agricultural lands. One approach is based on economic indicators, the other is on biophysical conditions. Both should follow principles of sustainable land management. Marginal land is an area where cost-effective production is not possible under given unfavourable environmental side conditions. These areas are defined as rural areas where farming conditions are more difficult due to natural constraints, which raise production costs and limit agricultural opportunities. Development of the rural areas, which are economically or biophysically marginalised is very important to preserve the socio-economic value of these areas and to contribute to food security, energy production and to maintain ecosystem services. High nature value farming, bioenergy crops and afforestation are highly recommended. As perceptions of marginal land are dynamic both in time and space, flexible policy and practical solutions are needed for their non-degrading use, which in any case shall support nature-based socioeconomic development.

Funding

This research was funded by European Commission, grant number 818346 called Sino-EU Soil Observatory for intelligent Land Use Management" (SIEUSOIL).

Authors' contributions

All authors contributed to the study conception and design. The first draft of the manuscript was written by Nándor Csikós and Gergely Tóth and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of Competing Interest

We have no conflict of interest to declare.

Data availability

No data was used for the research described in the article.

References

Abolina, E., Luzadis, V.A., 2015. Abandoned agricultural land and its potential for short rotation woody crops in Latvia. Land Use Policy 49, 435–445. https://doi.org/10.1016/J.LANDUSEPOL.2015.08.022.
Alexandratos, N., Bruinsma, J., 2012. World Agriculture towards 2030/2050: The 2012 Revision. WORLD Agric.
Baldock, D., Beaufoy, G., Brouwer, F., Godeschalk, F., 1996. Farming at the Margins. IEEP, LEI-DLO, London, The Hague.
Baude, M., Meyer, B.C., Schindewolf, M., 2019. Land use change in an agricultural landscape causing degradation of soil based ecosystem services. Sci. Total Environ. 659, 1526–1536. https://doi.org/10.1016/J.SCITOTENV.2018.12.455.
Benayas, J.M.R., Martins, A., Nicolau, J.M., Schulz, J.J., 2007. Abandonment of agricultural land: an overview of drivers and consequences. CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 2 https://doi.org/10.1079/PAVSNNR20072057.
Bertzky, M., Kapos, V., Scharlemann, J.P.W., 2011. Indirect Land Use Change from Biofuel Production: Implications for Biodiversity Prepared by. Peterborough.
Bindraban, P.S., Bulte, E.H., Conijn, S.G., 2009. Can large-scale biofuels production be sustainable by 2020? Agric. Syst. 101, 197–199. https://doi.org/10.1016/J.AGSY.2009.06.005.
Bouma, J., 1989. Using Soil Survey Data for Quantitative Land Evaluation 177–213. https://doi.org/10.1007/978-1-4612-3532-3_4.

Bouma, J., van Lanen, H.A.J., 1987. Transfer functions and threshold values: from soil characteristics to land qualities. In: Beek, K.J., Burrough, P.A., MacCormack, D.E. (Eds.), Proceedings of the International Workshop on Quantified Land Evaluation Procedures: Held in Washington, DC, 27 April - 2 May 1986. pp. 106–110.
Brandt, K., Glemnitz, M., 2014. Assessing the regional impacts of increased energy maize cultivation on farmland birds. Environ. Monit. Assess. 186, 679–697. https://doi.org/10.1007/s10661-013-3407-9.
Breure, A.M., De Deyn, G.B., Dominati, E., Eglin, T., Hedlund, K., Van Orshoven, J., Posthuma, L., 2012. Ecosystem services: a useful concept for soil policy making! Curr. Opin. Environ. Sustain. 4, 578–585. https://doi.org/10.1016/J.COSUST.2012.10.010.
Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality – A critical review. Soil Biol. Biochem. 120, 105–125. https://doi.org/10.1016/J.SOILBIO.2018.01.030.
Burrough, P.A., 1989. Fuzzy mathematical methods for soil survey and land evaluation. J. Soil Sci. 40, 477–492. https://doi.org/10.1111/J.1365-2389.1989.TB01290.X.
Cai, Ximing, Zhang, Xiao, Wang, Dingbao, 2011. Land availability for biofuel production. Environ Sci Technol 45, 334–339. American Chemical Society.
Claus, S., Taube, F., Wienforth, B., Svoboda, N., Sieleing, K., Kage, H., Senbayram, M., Dittert, K., Gericke, D., Pacholski, A., Hermann, A., 2014. Life-cycle assessment of biogas production under the environmental conditions of northern Germany: greenhouse gas balance. J. Agric. Sci. 152, 172–181. https://doi.org/10.1017/S0021859613000683.
Confalonieri, R., Jones, B., Van Diepen, K., Van Oorshoven, J., 2014. Scientific Contribution on Combining Biophysical Criteria Underpinning the Delineation of Agricultural Areas Affected by Specific Constraints: Methodology and Factsheets for Plausible Criteria Combinations.
Csikós, N., Szilassi, P., 2020. Impact of energy landscapes on the abundance of Eurasian skylark (Alauda arvensis), an example from North Germany. Sustainability 12, 664. https://doi.org/10.3390/su12020664.
Csikos, N., Schwanebeck, M., Kuhwald, M., Szilassi, P., Duttmann, R., 2019. Density of biogas power plants as an Indicator of bioenergy generated transformation of agricultural landscapes. Sustainability 11, 2500. https://doi.org/10.3390/su11092500.
Da La Rosa, D., Magaldi, D., 1982. Approxiamation to a Land Evaluation System with Special Reference to Mediterranean Regions. Sevilla.
Dale, V., Kline, K., Wiens, J., Fargione, J., 2010. Biofuels: Implications for Land Use and Biodiversity Biofuels: Implications for Land Use and Biodiversity.
Dauber, J., Brown, C., Fernando, A.L., Finnan, J., Krasuska, E., Ponitka, J., Styles, D., Thrän, D., Van Groenigen, K.J., Weih, M., Zah, R., 2012. Bioenergy from "surplus" land: environmental and socio-economic implications. BioRisk 7 5-50 7, 5–50. https://doi.org/10.3897/BIORISK.7.3036.
Domingues, R.R., Sánchez-Monedero, M.A., Spokas, K.A., Melo, L.C.A., Trugilho, P.F., Valenciano, M.N., Silva, C.A., 2020. Enhancing cation exchange capacity of weathered soils using biochar: feedstock, pyrolysis conditions and addition rate. Agron vol. 10, 824. https://doi.org/10.3390/AGRONOMY10060824.
Doran, J.W., Jones, A.J., Arshad, M.A., Gilley, J.E., 2018. Determinants of soil quality and health. Soil Qual. Soil Eros. 17–36 https://doi.org/10.1201/9780203739266-2.
Dumanski, J., Onofrei, C., 1989. Techniques of crop yield assessment for agricultural land evaluation. Soil Use Manag. 5, 9–15. https://doi.org/10.1111/J.1475-2743.1989.TB00754.X.
Duttmann, R., Schwanebeck, M., Nolde, M., Horn, R., 2014. Predicting soil compaction risks related to field traffic during silage maize harvest. Soil Sci. Soc. Am. J. 78, 408. https://doi.org/10.2136/sssaj2013.05.0198.
Dzatko, M., 1995. Recent development in land evaluation and sustainable land use planning in Slovakia. In: From Soil Suvey to Sustainable Farming. Soil Fertility Research Institute, Bratislava, pp. 203–210.
Elbersen, B., van Eupen, E., Mantel, S., Verzandvoort, S., Boogaard, H., Mucher, S., Cicarreli, T., Elbersen, W., Bai, Z., Iqbal, Y., von Cossel, M., McCallum, I., Carrasco, J., Ciria Ramos, C., Monti, A., Scordia, D., Eleftheriadis, I., 2017. D2.1. Definition and Classification of Marginal Lands Suitable for Industrial Crops in Europe. https://doi.org/10.5281/ZENODO.3539229.
Esch, E., MacDougall, A.S., Esch, E., MacDougall, A.S., 2018. More at the margin: leveraging ecosystem services on marginal lands to improve agricultural sustainability and slow trends of farming costs outpacing yield gains. AGUFM 2018, B33E–2714.
Esch, E., Mccann, K., Kamm, C., Arce, B., Carroll, O., Dolezal, A., Mazzorato, A., Noble, D., Fraser, E., Fryxell, J., Gilvesy, B., Canada, A., Krumholz, S., Campbell, M., Macdougall, A., 2021. Rising Farm Costs, Marginal Land Cropping, and Ecosystem Service Markets. Doi:10.21203/RS.3.RS-223049/V1.
FAO, 1976. A framework for land evaluation. FAO Soils Bull. 32.
FAO, 1983. Guidelines: land evaluation for rainfed agriculture. FAO Soils Bull. xii, 237.
FAO, 1985. Guidelines: land evaluation for irrigated agriculture. FAO Soils Bull. 55.
FAO, 1993. FESLM: an international framework for evaluating sustainable land management. World Resour. Rep. 73.
FAO, 2008. A Framework for Bioenergy Environmental Impact Analysis. Rome.
Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science (80) 319, 1235–1238. https://doi.org/10.1126/SCIENCE.1152747/SUPPL_FILE/FARGIONE.SOM.PDF.
Fórizsné, J., Máté, F., Stefanovits, P., 1972. Talajbonitáció - Földértékelés. MTA Agrártudományok Osztályának Közleményei 30, 359–378.
Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. Environ. Sci. Pol. 12, 491–503. https://doi.org/10.1016/J.ENVSCI.2009.01.006.
Godev, G., Klestov, V., 1971. Statistical evaluation of soil fertility at given plant environment system. In: UNDP/FAO 472 Meeting of Panel of Experts on Land Productivity Evaluation. Sofia.
Goldberg, S., 2008. Interaction of Aluminum and Iron Oxides and Clay Minerals and Their Effect on Soil Physical Properties: A Review, 20, pp. 1181–1207. https://doi.org/10.1080/00103629009368144.
Gopalakrishnan, G., Negri, M.C., Snyder, S.W., 2011. A novel framework to classify marginal land for sustainable biomass feedstock production. J. Environ. Qual. 40, 1593–1600. https://doi.org/10.2134/JEQ2010.0539.
Guerra, C.A., Maes, J., Geijzendorffer, I., Metzger, M.J., 2016. An assessment of soil erosion prevention by vegetation in Mediterranean Europe: current trends of ecosystem service provision. Ecol. Indic. 60, 213–222. https://doi.org/10.1016/J.ECOLIND.2015.06.043.
Haans, J.C.F.M., Heide, G., 1984. Dutch and German methods of soil survey interpretation: A critical comparison. In: Haans, J.C.F.M., Steur, G.G.L., Heide, G. (Eds.), Proceedings of the Seminar on Soil Survey and Land Evaluation. Wageningen.
Hamilton, G.J., Sheppard, J., Bowey, R., Fisher, P., 2016. Blade loosening creates a deeper and near-stable rooting zone that raises the productivity of a structurally unstable texture contrast soil. Soil Res. 55, 101–113. https://doi.org/10.1071/SR15364.
Hart, J.F., 2001. Half a century of cropland change. Geogr. Rev. 91, 525–543. https://doi.org/10.2307/3594739.
Helliwell, R., 2018. Where did the marginal land go? Farmers perspectives on marginal land and its implications for adoption of dedicated energy crops. Energy Policy 117, 166–172. https://doi.org/10.1016/J.ENPOL.2018.03.011.
Hollander, J.H., 1895. The concept of marginal rent. Q. J. Econ. 9, 175–187. https://doi.org/10.2307/1885598.
Hu, Y., Dai, J., Wang, R., 1999. GIS-based red soil resources classification and evaluation. Pedosphere 9, 131–138.
IIASA/FAO, 2012. Global Agro-ecological Zones (GAEZ v3.0).
Immerzeel, D.J., Verweij, P.A., van der Hilst, F., Faaij, A.P.C., 2014. Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy 6, 183–209. https://doi.org/10.1111/GCBB.12067.
James, L., 2010. Theory and identification of marginal land and factors determining land use change. Grad. Res. Master's Degree Plan B Pap. https://doi.org/10.22004/AG.ECON.98203.
Johnson, A.K.L., Cramb, R.A., Wegener, M.K., 1994. The use of crop yield prediction as a tool for land evaluation studies in northern Australia. Agric. Syst. 46, 93–111.
Jones, R., Le-Bas, C., Nachtergaele, F., Rossiter, D., Schulte, R., Van Velthuizen, H., 2014. Updated common bio-physical criteria to define natural constraints for agriculture in Europe - definition and scientific justification for the common biophysical criteria. JRC Sci. Policy Reports. https://doi.org/10.2788/79958.
Kang, S., Post, W.M., Nichols, J.A., Wang, D., West, T.O., Bandaru, V., Izaurralde, R.C., 2013. Marginal lands: concept, assessment and management. J. Agric. Sci. 5, p129 https://doi.org/10.5539/jas.v5n5p129.
Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation (A Guest Editorial). Soil Sci. Soc. Am. J. 61, 4–10. https://doi.org/10.2136/SSSAJ1997.03615995006100010001X.
Karmanov, I., Friyev, I., 1985. Site quality based on ecological soil indices. Soil Surv. L. Eval. 5, 40–48.
Khanna, M., Chen, L., Basso, B., Cai, X., Field, J.L., Guan, K., Jiang, C., Lark, T.J., Richard, T.L., Spawn-Lee, S.A., Yang, P., Zipp, K.Y., 2021. Redefining marginal land for bioenergy crop production. GCB Bioenergy 13, 1590–1609. https://doi.org/10.1111/GCBB.12877.
Klingebiel, A.A., Montgomery, P.H., 1961. Land-Capability Classification. Soil Conservation Service. U.S. Dept. of Agriculture, Washington D.C.
Koreleski, K., 1988. Adaptations of the Storie index for land evaluation in Poland. Soil Surv. L. Eval. 8, 23–29.
Kreybig, L., 1935. Richtlinien der Bodenbonitierung und die Bodenkartierung im Dienste der praktishen Landwirchaft. Congr. Soil Sci. I.
Kumar, R.K., Kalbande, A.R., Landey, R.J., Yadav, S., 1984. Soil evaluation for agricultural land Us_II. Productivity potential appraisal. J. Indian Soc. Soil Sci. 32, 467–472.
Lal, R., 1991. Tillage and agricultural sustainability. Soil Tillage Res. 20, 133–146. https://doi.org/10.1016/0167-1987(91)90036-W.
Liu, S.L., Dong, Y.H., Li, D., Liu, Q., Wang, J., Zhang, X.L., 2013. Effects of different terrace protection measures in a sloping land consolidation project targeting soil erosion at the slope scale. Ecol Eng 53, 46–53. Elsevier.
MacHmuller, M.B., Kramer, M.G., Cyle, T.K., Hill, N., Hancock, D., Thompson, A., 2015. Emerging land use practices rapidly increase soil organic matter. Nat. Commun. 61 (6), 1–5. https://doi.org/10.1038/ncomms7995.
Magaldi, D., Ronchetti, G., Haans, J.C.F.M., 1984. Report on developing project for land evaluation in Italy on a 1:1 million scale. In: Steur, G.G.L., Heide, G. (Eds.), Proceedings of the Seminar on Soil Survey and Land Evaluation. Wageningen, pp. 57–63.
MAGIC, 2022. Marginal Lands for Growing Industrial Crops [WWW Document]. URL. https://magic-h2020.eu/.
Makhdoum, M.F., 1993. First application of automated land evaluation in Iran. Environ. Manag. 173 (17), 409–419. https://doi.org/10.1007/BF02394683.
Masud, M.M., Li, J.Y., Xu, R.K., 2014. Use of alkaline slag and crop residue biochars to Promote Base saturation and reduce acidity of an acidic Ultisol. Pedosphere 24, 791–798. https://doi.org/10.1016/S1002-0160(14)60066-7.
Máté, F., 1960. Megjegyzések a talajok termékenységük szerinti osztályozásához. Agrokém. Talajt. 9, 419–426.

Milbrandt, A., Overend, R.P., 2008. Assessment of Biomass Resources from Marginal Lands in APEC Economies, August 2009. url. http://www.nrel.gov. date acces: 05.02.2022.
Mooney, D.F., Barham, B.L., Lian, C., 2015. Inelastic and fragmented farm supply response for second-generation bioenergy feedstocks: ex ante survey evidence from Wisconsin. Appl. Econ. Perspect. Policy 37, 287–310. https://doi.org/10.1093/AEPP/PPU033.
Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob. Food Sec. 14, 1–8. https://doi.org/10.1016/J.GFS.2017.01.001.
Muscat, A., de Olde, E.M., Candel, J.J.L., de Boer, I.J.M., Ripoll-Bosch, R., 2022. The promised land: contrasting frames of marginal land in the European Union. Land Use Policy 112, 105860. https://doi.org/10.1016/J.LANDUSEPOL.2021.105860.
Petersen, B., Snapp, S., 2015. What is sustainable intensification? Views from experts. Land Use Policy 46, 1–10. https://doi.org/10.1016/J.LANDUSEPOL.2015.02.002.
Peterson, G.M., Galbraith, J.K., 1932. The concept of marginal land. Am. J. Agric. Econ. 14, 295–310. https://doi.org/10.2307/1230112.
Plieninger, T., Gaertner, M., 2011. Harnessing degraded lands for biodiversity conservation. J. Nat. Conserv. 19, 18–23. https://doi.org/10.1016/J.JNC.2010.04.001.
Ricardo, D., 1817. On the Principles of Political Economy and Taxation. J. M. Dent and Sons, London.
Riquier, J., Bramao, D.L., Cornet, J.P., 1970. A new system of soil appraisal in terms of actual and potential productivity. FAO Soil Resour. Dev. Conserv 70 (6), 1–38.
Rossiter, D.G., 1996. A theoretical framework for land evaluation. Geoderma 72, 165–190. https://doi.org/10.1016/0016-7061(96)00031-6. Elsevier.
Ruskule, A., Nikodemus, O., Kasparinskis, R., Bell, S., Urtane, I., 2013. The perception of abandoned farmland by local people and experts: landscape value and perspectives on future land use. Landsc. Urban Plan. 115, 49–61. https://doi.org/10.1016/J.LANDURBPLAN.2013.03.012.
Sanchez, P.A., Couto, W., Buol, S.W., 1982. The fertility capability soil classification system: interpretation, applicability and modification. Geoderma 27, 283–309. https://doi.org/10.1016/0016-7061(82)90019-2.
Schroers, J.O., 2006. Zur Entwicklung der Landnutzung auf Grenzstandorten in Abhängikeit agrarmarktpolitischer, Agrarstrukturpolitischer und Produktions-Technologischer Rahmenbedingungen.
Schubert, R., Schellnhuber, H.J., Buchmann, N., Epiney, A., Grieβhammer, R., Kulessa, M., Messner, D., Rahmstorf, S., Schmid, J., 2008. Future Bioenergy and Sustainable Land Use. WBGU, Berlin.
Shao, X.N., 1984. Land evaluation in China. Soil Surv. L. Eval. 4, 39–43.
Shortall, O.K., 2013. "Marginal land" for energy crops: exploring definitions and embedded assumptions. Energy Policy 62, 19–27. https://doi.org/10.1016/J.ENPOL.2013.07.048.
Sigmond, E., 1935. A birtokpolitikai tervek és a talaj belső értékének meghatározása. Köztelek 44, 1003–1007.
Sisov, L.L., Durmanov, D.N., Karmanov, I.I., Yeframov, V.V., 1991. Teoreticseszkije osznovü i prakticseszkije szredsztva izmenenija plodorogia pocsvü. Agropromizdat, Moscow.
Storie, R.E., 1976. Storie Index Soil Rating, Special Publication Division of Agricultural Science. University of California, Berkley.
Strijker, D., 2005. Marginal lands in Europe—causes of decline. Basic Appl. Ecol. 6, 99–106. https://doi.org/10.1016/J.BAAE.2005.01.001.
Suzuki, S., Noble, A.D., Ruaysoongnern, S., Chinabut, N., 2007. Improvement in Water-Holding Capacity and Structural Stability of a Sandy Soil in Northeast Thailand., 21, pp. 37–49. https://doi.org/10.1080/15324980601087430.
Svoboda, N., Taube, F., Kluß, C., Wienforth, B., Kage, H., Ohl, S., Hartung, E., Herrmann, A., 2013. Crop production for biogas and water protection-A trade-off? Agric. Ecosyst. Environ. 177, 36–47. https://doi.org/10.1016/j.agee.2013.05.024.
Sys, C., 1985. Land Evaluation. I-II-III. State University of Ghent, Ghent.
Tang, Y., Xie, J.S., Geng, S., 2010. Marginal land-based biomass energy production in China. J. Integr. Plant Biol. 52, 112–121. https://doi.org/10.1111/J.1744-7909.2010.00903.X.
Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. U. S. A. 108, 20260–20264. https://doi.org/10.1073/PNAS.1116437108/-/DCSUPPLEMENTAL.
Tógyer, T.N., 2012. Characteristics of arable land valuation in Hungary. Theory Methodol. Pract. 8, 95–100.
Tógyer, T.N., 2012. Characteristics of Arable Land Valuation in Hungary. In: Theory Methodol Pract, 8. Faculty of Economics, University of Miskolc, pp. 95–100.
Tóth, G., Ivits, E., Laborczi, A., Mészáros, J., Szabó, B., Pásztor, L., 2021. Impact of land quality on land productivity trends in Hungary. EGU21. https://doi.org/10.5194/EGUSPHERE-EGU21-7930.
Trashliev, H., Godev, G., Krastanov, S., Klevstov, A., Kabakchiev, I., Hershkovich, E., Dilkov, D., 1971. Assessment of ecological conditions for wheat and maize in Bulgaria by means of multivariate regression analysis. In: UNDP/FAO 472 Meeting of Panel of Experts on Land Productivity Evaluation. Sofia.
Unger, P.W., Kaspar, T.C., 1994. Soil compaction and root growth: a review. Agron. J. 86, 759–766. https://doi.org/10.2134/AGRONJ1994.00021962008600050004X.
USDA, 1951. Soil Survey Manual. Agricultural Handbook No. 18. Washington DC.
USDA-NRCS, 2010. National Soil Survey Handbook 430-VI. [WWW Document]. URL. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054242.
Van Kernebeek, H.R.J., Oosting, S.J., Van Ittersum, M.K., Bikker, P., De Boer, I.J.M., 2016. Saving land to feed a growing population: consequences for consumption of crop and livestock products. Int. J. Life Cycle Assess. 21, 677–687. https://doi.org/10.1007/S11367-015-0923-6/FIGURES/7.
Van Lanen, H.A.J., Broeke, M.J.D.H., Bouma, J., de Groot, W.J.M., 1992. A mixed qualitative/quantitative physical land evaluation methodology. Geoderma 55, 37–54.
Wells, G.J., Stuart, N., Furley, P.A., Ryan, C.M., 2018. Ecosystem service analysis in marginal agricultural lands: a case study in Belize. Ecosyst. Serv. 32, 70–77. https://doi.org/10.1016/J.ECOSER.2018.06.002.
Wiegmann, K., Hennenberg, K.J., Fritsche, U.R., 2008. Joint International Workshop on High Nature Value Criteria and Potential for Sustainable Use of Degraded Lands, Degraded Land and Sustainable Bioenergy Feedstock Production-Issue Paper-Authors.
WOCAT, 2022. WWW Document. URL. https://qcat.wocat.net/en/wocat/list/?type=technologies (accessed 3.22.22).
Wood, S., Sebastian, K., Scherr, S.J., 2000. Pilot Analysis of Global Ecosystems: Agroecosystems. International Food Policy Research Institute and World Resources Institute.
Yang, P., Zhao, Q., Cai, X., 2020. Machine learning based estimation of land productivity in the contiguous US using biophysical predictors. Environ Res Lett 15. IOP Publishing, 074013.
Zanetti, F., Alberghini, B., Marjanović Jeromela, A., Grahovac, N., Rajković, D., Kiprovski, B., Monti, A., 2021. Camelina, an ancient oilseed crop actively contributing to the rural renaissance in Europe. A review. Agron. Sustain. Dev. 411 (41), 1–18. https://doi.org/10.1007/S13593-020-00663-Y.
Zhang, Q., Ma, J., Qiu, G., Li, L., Geng, S., Hasi, E., Li, C., Wang, G., Li, X., 2012. Potential energy production from algae on marginal land in China. Bioresour Technol 109, 252–260. https://doi.org/10.1016/J.BIORTECH.2011.08.084. Elsevier.
Zhu, X., Liang, C., Masters, M.D., Kantola, I.B., DeLucia, E.H., 2018. The impacts of four potential bioenergy crops on soil carbon dynamics as shown by biomarker analyses and DRIFT spectroscopy. GCB Bioenergy 10, 489–500. https://doi.org/10.1111/GCBB.12520.
Zuazo, V.H.D., Pleguezuelo, C.R.R., 2009. Soil-Erosion and runoff prevention by plant covers: A review. Sustain. Agric. 785–811. https://doi.org/10.1007/978-90-481-2666-8_48.