

Identifying non-agricultural marginal lands as a route to sustainable bioenergy provision - A review and holistic definition

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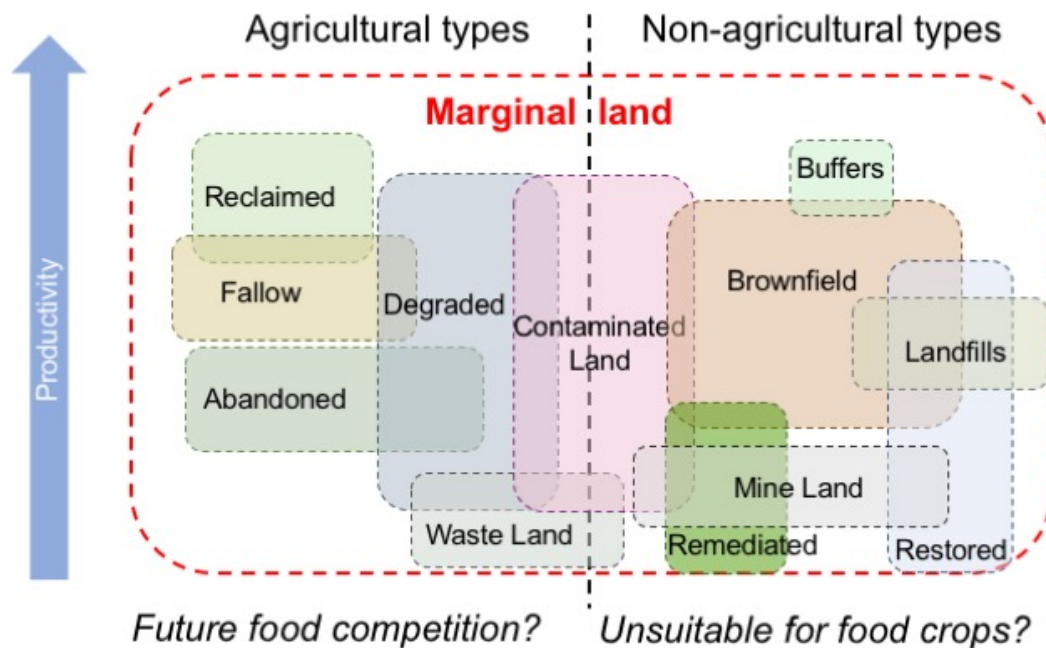
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Abstract

Concerns regarding global food security, direct or indirect land use change from bioenergy production require a better understanding of the alternative landbanks that may exist. The potential of 'marginal' land, whether for food or fuel production, has been the subject of much previous research but is currently compromised by the lack of a clear, globally accepted definition. A critical omission in the plethora of existing explicit or implicit definitions in use is the lack of comprehensive or consistent inclusion of non-agricultural land types, here re-defined as those now rendered unsuitable, unacceptable or permanently unavailable for food purposes. The result is variable inclusion of such land types in different areal studies, uncertainty regarding the nature of any land identified as 'marginal', in turn leading to inconsistent estimates of the role they could play in the provision of sustainable bioenergy.

The purpose of this research is to review the full range of possible 'marginal' land resources, especially those which are non-agricultural so avoid food competition, from previously-developed brownfield land, to former landfills or old mineral workings. Literature examples are compared to determine which land types have actually been included and quantified. In

these case studies, non-agricultural types may equal other marginal lands at country or provincial scale, becoming dominant in urban regions. An inclusive definition is proposed, together with a graphic classification scheme, to guide future studies and enable quantification of truly non-agricultural marginal land as a potential contribution to sustainable bioenergy provision as part of the net zero, circular economy.

Highlights

- Inconsistent definitions or inclusion has neglected certain marginal land types
- Non-agricultural areas may equal other marginal lands types at regional scale
- Non-agricultural marginal lands may be 15-24% of urban regions
- Use for bioenergy could avoid food competition and (in)direct land use conflicts

Keywords: Biofuels; Indirect Land Use Change; Brownfield; Food versus fuel;

Word count: 9,769

Abbreviations: MHa = mega hectare = 10^6 Ha;

1. Introduction

The importance of renewable energy in mitigating human induced climate change has long been established [1]. The necessity for change has been recognised by governments [2,3] and has impacted policy, driving research, development and rapid deployment of alternative, renewable energy technologies [4]. Having a broad energy mix is most likely to be the best method to achieve energy and climate change targets [5]. Bioenergy has been championed as a major contributor to this mix as a substitute to fossil fuels that can serve as a sink to capture and store atmospheric carbon [6]. Furthermore, bioenergy has been identified as a potential solution which could not only help mitigate climate change and provide energy security but also promote rural development [7][8]. Biomass can be readily substituted for fossil fuels, with the ability to utilise pre-existing power generation and distribution infrastructure [9], and is a versatile source of renewable energy, capable of providing both electricity and heat [10]. Demands for low carbon energy has seen global biomass production increase dramatically in recent years [11] and bioenergy currently represents 80% of the global renewable energy mix [9]. This demand is set to continue increasing as it is predicted bioenergy could supply up to a third of global primary energy supply by 2050 [12]. For example, biomass is currently the largest single source of renewable energy in the conterminous United States, with the largest future potential source predicted to come from growing dedicated energy crops on agricultural land [13]. When combined with carbon capture and storage bioenergy also offers a significant negative emissions technology, provided acceptable land resources for biomass production are available over suitable CO₂ storage basins [14].

More biomass will be needed to achieve ambitious renewable energy and climate stabilization targets [11] but production and consumption must be sustainable if bioenergy is to be successful [6]. However, reaching consensus on a definition of biomass sustainability is both challenging and elusive [15,16]. A common theme for biomass to be considered sustainable is that it must be cultivated and harvested in a sustainable way, considering the full chain of production activities from growing feedstock to final energy conversion [17]. The sustainability of bioenergy is inextricably linked to its requirement for land for production, as an increasing demand for biomass inevitably leads to an increased demand for land on which energy crops could be grown [18]. The extensive spatial footprint of bioenergy [19] is problematical and it has become a priority to find locations where biomass can be grown sustainably.

For biomass to be considered sustainable it should deliver lifecycle greenhouse gas emission savings [20] and an important aspect of this is ensuring it is not grown on land with high carbon stock or biodiversity value [20]. Issues arise, however, when the conversion to agriculture or energy crops of land types with high carbon stock is considered [21]. As Fargione et al. [22] explain, the conversion of rainforests, peatlands, savannas, or grasslands to produce crop-based biofuels can create a 'biofuel carbon debt'. The amount of carbon dioxide released during this conversion has been quantified as 17 to 420 times greater than that saved in annual greenhouse gas reductions created by the displacement of fossil fuels [22]. Any large-scale land conversion for bioenergy crops will also have implications on global food security and existing ecosystem services [23,24].

There are further concerns relating to the use of existing agricultural land for bioenergy production, as the use of fertile land currently in use for food crops leads to the clearing of

carbon rich or biodiverse land elsewhere in the world to meet displaced demand for food crops [25]. This indirect land use change impact of bioenergy production can lead to biodiversity loss, rising food prices [25], and additional greenhouse gas emissions which lead to doubts about the climate benefits of bioenergy as a source of renewable energy [7]. Searchinger et al [26] warn that indirect land use change associated with increased corn-based ethanol demand could potentially lead to a doubling of greenhouse gas emissions in the next 30 years [26]. The credibility of such claims has been labelled an over-simplification, with counter claims arguing that carbon emissions associated with indirect land use change are far too complicated to be portrayed in pre-existing models and that the motivation for people clearing land cannot be so easily quantified [6,21]. However, the beneficial impacts of biomass crops, such as the carbon sequestration in soil and root biomass, are overshadowed once the effects of land use change, both direct and indirect, begin to be considered [27].

The challenge of identifying a suitable amount of land whilst also ensuring sustainable food production and environmental protection is known as the bioenergy land use dilemma [28]. As outlined above, land use decisions relating to biomass production can have significant effects on carbon sequestration, native plant diversity, food production, greenhouse gas emissions, water, and air quality [6]. It has been argued that a requirement for sustainable biomass production is not only the avoidance of carbon rich areas but avoidance of agricultural land that would otherwise be used for food production [7]. The consideration of land types that are not used for food provision would not only strengthen food security [23] but has also become an imperative to realise the greenhouse gas emission savings that bioenergy could provide [6]. For these reasons studies have emerged highlighting the need to further an understanding of the role idle, abandoned, or degraded land types could play in bioenergy provision [7,29] and these land categories have since become associated with the term ‘marginal’ land.

The aim of this paper is to critically assess the evolving concept of ‘marginal’ land with respect to its potential to deliver sustainable bioenergy provisioning services. In particular, the focus is on the range of non-agricultural land types that have, or perhaps should, be included in existing, or future, areal studies of marginal land. The working hypothesis is that truly “non-agricultural” land areas can be identified which offer an alternative to future direct competition with food production or indirect land use change from utilising marginal agricultural land.

2. Materials and methods

A review of published academic literature was used to achieve two objectives: Firstly a critical review of the theoretical development of the marginal land concept, the changing use of the term, purported benefits of using this land resource, limitations and problematic nature of the terminology; secondly, a quantitative (i.e. land areas) and qualitative (i.e. land types) evaluation of marginal land resource assessment studies that have included non-agricultural land types. From these a comprehensive taxonomy and summary of the unique advantages and challenges of using these land resources have been compiled.

The initial data review was conducted between 2014 – 2018 [30], considering any articles written within the last 20 years, then updated in late 2019 and early 2020. A combination of Google Scholar and Scopus were searched using the Boolean search terms ‘bioenergy’ OR ‘biomass’ OR ‘biofuel’ AND ‘availability’ AND ‘marginal land’ to locate studies assessing the availability of marginal land. The methodology sections of selected articles were scrutinised to identify the types of land that were included. Only those studies that specifically considered

non-agricultural land were considered further. For example, those using any of the following keywords: ‘vacant’, ‘derelict’, ‘abandoned’, ‘mine land’, ‘landfill’, ‘brownfield’ and ‘buffers’.

For each case study the qualitative data collected were the location, the definition of marginal land employed and a list of the non-agricultural land types that have been included. This was also used as the basis of a new graphical classification scheme. Quantitative data were compiled on the area of all types of marginal land and the area of non-agricultural land types. These were used to calculate the relative importance of agricultural and non-agricultural types as a percentage of all marginal land and of the total area of land considered.

3. Theory of ‘marginal land’ – a critique and proposed revision of the state-of-the art

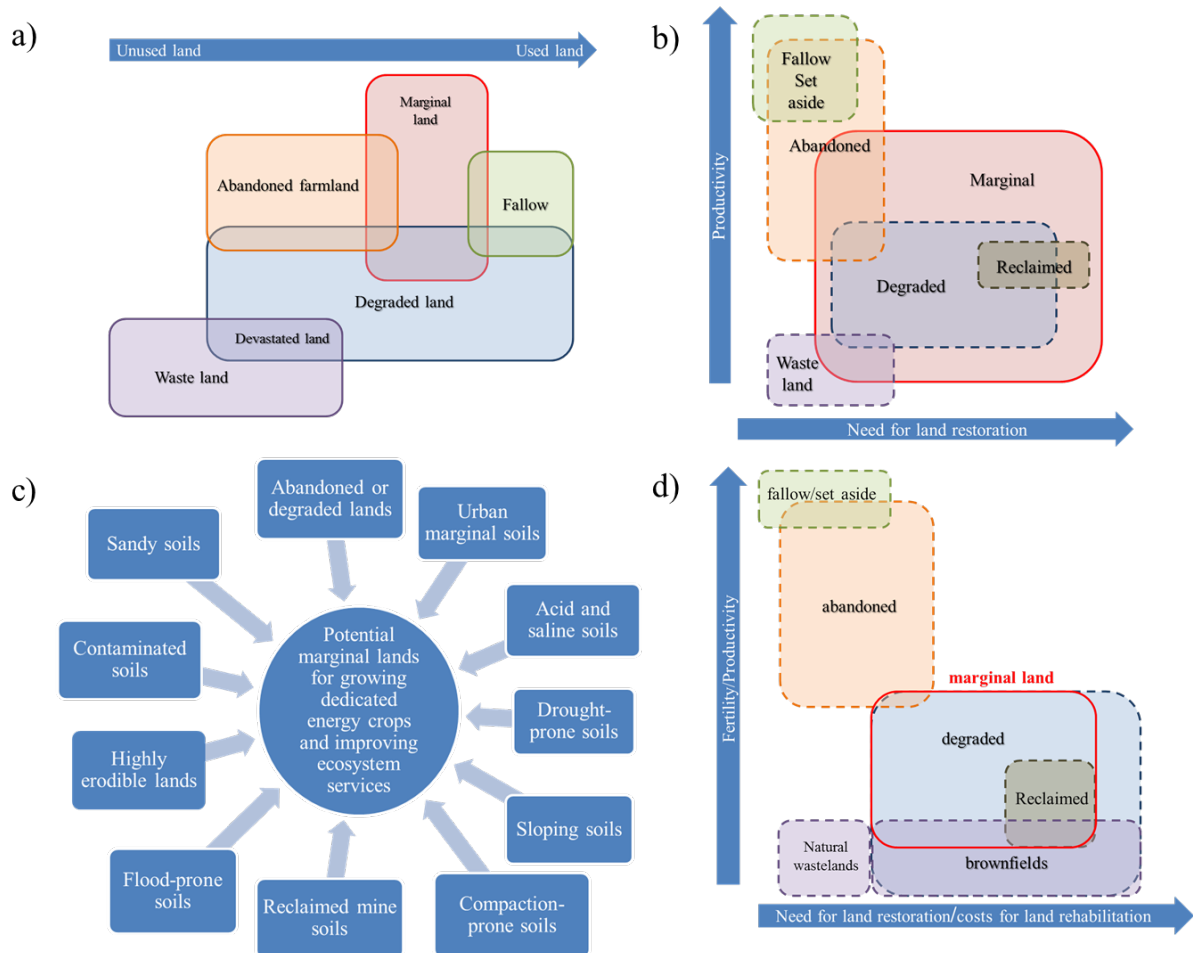
3.1 Emergence of the ‘marginal’ land concept

According to Smit et al. [31], the marginality of land ‘relates fundamentally to the economic viability of land uses’ and can be used to define areas in agriculture which have limited productive potential. The term ‘marginal’ land originally emerged from the field of agricultural economics in the 19th Century [32], with Ricardo [33] using the categorisation in his land rent theory, which became the foundation of marginal productivity theory. Marginal lands were at the ‘margins of cultivation’ [34], at the margin of economic viability [35], and ‘where cost-effective production is not possible under given conditions’ [36]. For example “Marginally Suitable”) was the United Nations Food and Agriculture Organisation’s lowest Land Suitability Class (S3) defined as “Land having limitations which in aggregate are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified.” [37]. These three core aspects of severe limitations, the requirements for additional inputs and the marginal net benefit obtained became part of the definition of marginal land proposed by the UN Consultative Group on International Agricultural Research, to which were added “Limited options for diversification...” and “...risks of irreversible degradation.” [38] The definition compared marginal with favoured, fragile and degraded land types on the basis of biophysical and socio-economic constraints [39]. Thus, whilst land was originally deemed marginal purely from an economic perspective, the definition of marginal land broadened to include environmental factors such as soil health and topography [27]. Increasingly marginal land has become an ‘umbrella term’ to describe idle, barren, degraded, abandoned and underutilised lands [40] with the concept evolving across time, space and discipline [32].

3.2 Visualising marginal and related land types

Several authors have attempted to illustrate the concept of marginal land and its complex relation to other similar land types using Euler diagrams [29,40,41]. Comparison of these examples reveals subtle differences in how marginal lands are viewed by different authors in the context of bioenergy production (Fig. 1).

Fig. 1. Variation in diagrams used to illustrate land that could be considered ‘marginal’ compared to other similar or overlapping types. **a)** An early (2008) schematic diagram according to Wiegmann et al. [29]. **b)** An alternative later (2012) diagram according to Dauber et al. [40], with reclaimed land now included. **c)** Further land types that have been considered as marginal land for potentially growing dedicated energy crops according to Blanco-Canqui [42]. **d)** A more recent (2016) schematic diagram, now including brownfields, used by SEEMLA [41] to contextualise conditions of four pilot sites. Adapted from [29], [40], [42], and [41].



3.2.1 Marginal lands

Wiegmann et al. [29] define marginal land in terms of land economics, which they depict as partially overlapping degraded, abandoned and fallow land (see Fig.1a). In contrast Dauber et al.’s [40] version (Fig. 1b) represents marginal land as fully encompassing degraded and reclaimed land types, whilst separate from fallow and set aside lands. More recently, the EU funded SEEMLA project ‘Sustainable Exploitation of Biomass for Bioenergy from Marginal Land’ [41] has adapted Dauber et al.’s [40] figure to contextualise the condition of four pilot sites [41]. In the new figure (Fig. 1d) marginal land no longer fully encompasses degraded land and now includes some brownfield sites. Finally, Blanco-Canqui et al. [42] present an illustration (Fig. 1c) that suggests potential marginal lands for growing dedicated energy crops could include an even wider range of land types from urban marginal soils to contaminated soils. These studies, and their associated schematic diagrams, illustrate the variability in how marginal land is defined, its increased prominence in classification schemes and the tendency

for it now to be understood as more of an umbrella term than the initial economic definition intended.

3.2.2 Fallow land or set-aside

Fallow land is temporarily unused farmland if during part of a crop cycle [29] but is set-aside land if this is due to political intervention [40]. It overlaps with marginal land in Fig 1 (a), whereas fallow/set aside sites are grouped together in (b) and (d), shown overlapping with abandoned land but not considered marginal. So, a fallow land area might be considered marginal under (a), even if not abandoned or degraded but would be excluded from marginal land if using either schemes (b) or (c).

3.2.3 Abandoned land (farmland)

In abandoned farmland agricultural activities have ceased for economic, political or environmental reasons [29,40]. For land that had been farmed but is now permanently abandoned this could be because it is either degraded, marginal, both or neither in scheme Fig 1 (a), whereas in scheme (b), it could be neither, both or just marginal. However, in (d) it would only be considered marginal land if it was also degraded.

3.2.4 Waste lands

These are natural lands rendered permanently and naturally unusable by unfavourable physical and biological conditions [29]. If they are also degraded then they are referred to devastated in Fig 1(a). Some waste lands are included as marginal land in (b), which may or may not also be degraded, but are excluded in (a). In (d) wastelands are separately classed as “natural” so do not include degraded land, nor are they ever considered as marginal lands.

3.2.5 Degraded lands

Degraded lands [38] are in essence those where current productive use has been limited anthropogenically, although definitions vary [29,40]. In Fig 1 (a) these are regarded as a separate class, potentially overlapping with either abandoned, marginal, fallow or waste lands. In contrast, all degraded lands would be considered as marginal in scheme (b), together with most of those that were not also brownfields in (d). Thus, degraded areas might all be included or some excluded from marginal land if using different schemes.

3.2.6 Brownfields

Brownfields are previously-developed areas that may or may not be affected by potential contamination issues, depending on the respective national definition [43]. Brownfields are only considered separately in Fig (d), here as a subset of degraded land. Presumably they are either not considered in schemes (a) or (b), are not distinguished from other types of marginal land, so would not necessarily be included as marginal land.

3.2.7 Reclaimed lands

Reclaimed lands are strictly those recovered from below water level by land-raising, but in this context have also referred to those restored after mining or other non-agricultural use [40], possibly including remediated brownfields or contaminated land. Reclaimed lands are only shown in Fig 1 (b) and (d) they are shown as a subset of marginal lands in both cases but may not be degraded in (b) and could be from the restoration of brownfields in (d).

3.2.8 Implications of inconsistent schemes

The descriptions and scenarios above show that the subtle differences observed between graphical schemes are substantive. It may be noted that the number of categories used increases from 5 through 6 to 7 over an 8 year period for the sources cited, which may indicate attempts to refine and adjust the classifications sequentially. Although these each offer a useful visual aid of the marginal land paradigm, in an operational context the subtle differences between them would lead to the same land parcel being classified differently using different schemes. Critically, this might also lead to variability in whether it was classified as marginal lands or included in any areal survey thereof.

3.3 Purported benefits of marginal lands for bioenergy

Regardless of the definition employed, studies tend to reference a similar set of potential benefits of using marginal land for bioenergy provision. It is argued that because marginal land is largely unsuitable for agriculture it could avoid many of the competition effects of direct and indirect land use change which is currently bringing the sustainability of bioenergy into disrepute [10]. Fargione et al. [22] have even claimed that if biofuels are from biomass waste or perennial crops grown on abandoned and degraded agricultural lands they ‘incur little or no carbon debt and can offer immediate and sustained greenhouse gas advantages’ [22]. In cases where marginal land has poor vegetation cover it has been suggested that utilisation for energy crop purposes can increase the amount of sequestered carbon in soil and root biomass [27,44]. If non-agricultural lands are amended with organic waste material these can provide decadal benefits, easily exceeding the requirements of 4 per mille initiative and the Paris agreement [45]. Furthermore, it has been proposed that utilising these marginal lands can enhance their environmental condition [6] by improving soil fertility, reducing degradation, reducing wind and water erosion and providing biodiversity conservation [10,42,46,47] and habitat quality benefits [48]. Studies have also claimed that utilising marginal lands could bring additional societal benefits such as increased rural employment and improved scenery and infrastructure [6,46].

3.4 Attempts to quantify ‘marginal’ land

As Lewis and Kelly [28] point out, since 1993 there has been a large increase in the number of papers addressing terms such as marginal lands and biofuels in combination with methodological terminology including GIS and spatial data analysis. Such attempts have taken place at various scales, using a variety of models and data inputs [28]. There are a number of studies that have attempted to identify the availability of marginal land at the global level [49–52]. The earlier of these studies [49,50] compare past and current land cover using a global scale database to identify abandoned agricultural areas. Cai et al. [51] attempted to apply land suitability indices based on soil productivity, topography, soil temperature regime and humidity. These indices were then combined with land cover mapping in an attempt to understand the current land use of areas deemed marginal based on the land suitability indices. As Lewis and Kelly [28] argue, these global scale studies are challenged by the availability of up-to-date datasets at a suitable resolution. Similar obstacles exist for the growing number of studies seeking to identify the amount of marginal land at a national or regional level. There have been a few attempts to identify marginal land nationally: Studies have considered the United States [53] and Australia [54], with several seeking to understand the extent of this resource in China [46,55–61] due to this country’s pressing need to avoid growing bioenergy

crops on agricultural land [28]. There have also been a range of studies at a regional scale, in particular several assessments have been attempted in the United States [27,62–67] and Italy [68–70]. Fewer studies so far have applied these methods in developing countries. Milbrandt et al. [71] conducted a semi-global assessment of the provision of marginal land in Asian-Pacific Economic Cooperation countries which included developing countries of South-East Asia. Studies have also investigated the availability of marginal land in Sub-Saharan Africa [72] and India [73,74].

3.5 Ambiguities in ‘marginal’ land definitions

A number of other researchers have underlined key issues and related assumptions [75] with the term that brings into question its role as a sustainable option for bioenergy production or hampers attempts to identify the land resource. The most pronounced problem is related to the variation and ambiguity in its definition or understanding. The definition varies widely according to country, local conditions and the organisation or institution studying the issue [21,76,77], while the underlying concept of marginal lands has evolved and been used interchangeably with other terms [32]. Often the classification schemes used to identify marginal land (such as shown in Fig. 1) vary significantly leading to various interpretations as to what land types can be classed as marginal. As Wicke [10] explains, the vagueness of the classification of this land type leads to practical difficulties in identifying marginal land. This, coupled with dissimilarities in model and datasets applied [28], has led to a wide range of estimates regarding the availability of land for growing dedicated energy crops [78]. In the UK, for example, published estimates of the extent of marginal land resource range from 362,859 ha [23] to 3.1 Mha [79]. Moreover, Glithero et al. [78] consider these estimates to be maxima, given the limited number of farmers who would actually be willing to take up energy crop production in the current context of dedicated energy crop growth in England. The marginal land label further dissuades farmers from involvement as they are keen not to pronounce their land as being marginal ‘enough’ for this purpose only [80]. The various ways in which the term has been approached makes comparisons of studies difficult [7] and therefore the appropriateness of the land resources identified are brought into question. Wicke [10] argues that the ambiguity of the definition must be removed by the establishment of clear criteria and a methodology for identifying land that is sustainable for bioenergy production. At present this is lacking in the marginal land discourse which leads to questions regarding the certainty of identified land being an acceptably sustainable solution to the bioenergy land use dilemma.

Shortall [75] identifies three dominant definitions of the term marginal land and outlines the problematic technical, normative, and political assumptions that are embedded within each of them: The first two definitions - that marginal land represents either ‘land unsuitable for food production’ or ‘ambiguous lower quality land’ share the same assumptions. Both assume that there is enough of these land types, that production is possible on them, and that they can be targeted [75]. However, such assumptions are particularly problematic when the definition still contains a degree of ambiguity and could still represent several different land types from the most degraded agricultural land to brownfield land. The third definition, that marginal land is ‘economically marginal land’ has a different set of assumptions and related problems. Shortall [75] explains that it is assumed that using economically marginal land for bioenergy production is possible in a sustainable way without competing with food production. However, the author points out that using land types such as grade 3 or 4 (i.e. good to moderate, or poor) agricultural land would, in fact, still lead to the displacement of some food production [75]. Similarly, Kang

et al. [32] argue that marginal land already plays an important role for agriculture, noting that it was the primary factor behind a 25% increase in global wheat production in 1997. It is the temporality and variability of the economic based definition that is particularly challenging when trying to gain an understanding of the role marginal land could play in providing sustainable bioenergy. Li et al [81] argue that marginalization of agricultural land may be a dynamic effect consequent on rapid urbanization in China. Shortall [75] explains that what is considered marginal for one crop under one set of economic conditions may not be marginal for another crop or in other conditions, since what is at the economic margin of production at one point in time may be considered not marginal as prices of harvesting, transport or production fluctuate. Dauber et al. [40] touch on a similar theme by arguing that using land that is temporarily idle could still be contributing to indirect land use change if that land could have come back into use for agriculture at a later date. Evidentially, there is a lack of clarity with regards to the type of land that is being referred to in many studies and, as Shortall [75] concludes, depending on the definition employed, using marginal land could be arguably either unfeasible, due to poor quality land, or unsustainable, due to a continuation of detrimental land use change.

3.6 Problems identifying and using ‘marginal’ land

From an operational perspective, marginal land poses a challenge to identify. Dale et al. [21] discuss the difficulty in utilising satellite imagery to find marginal land. This is made even more difficult if the definition of the resource sought remains ambiguous. It is often assumed that land is idle [10] yet it is problematic to assume this from land cover data or poor resolution satellite imagery. Some uses are particularly difficult to identify such as grazing or fuelwood collection [40]. Lewis and Kelly [28] state that hard-to-detect land uses can often not be captured via remote sensing which ultimately leads to them being left out of broad scale geospatial datasets. This is of particular concern when the often wide-reaching definition of marginal land is taken into consideration and could arguably lead to fears that some land types are being overlooked. A recent review of methods used in marginal land assessment suggested that biophysical and socio-economic factors needed to be qualified by consideration of qualitative data, such as the landowner’s perspective on whether the land was marginal [82].

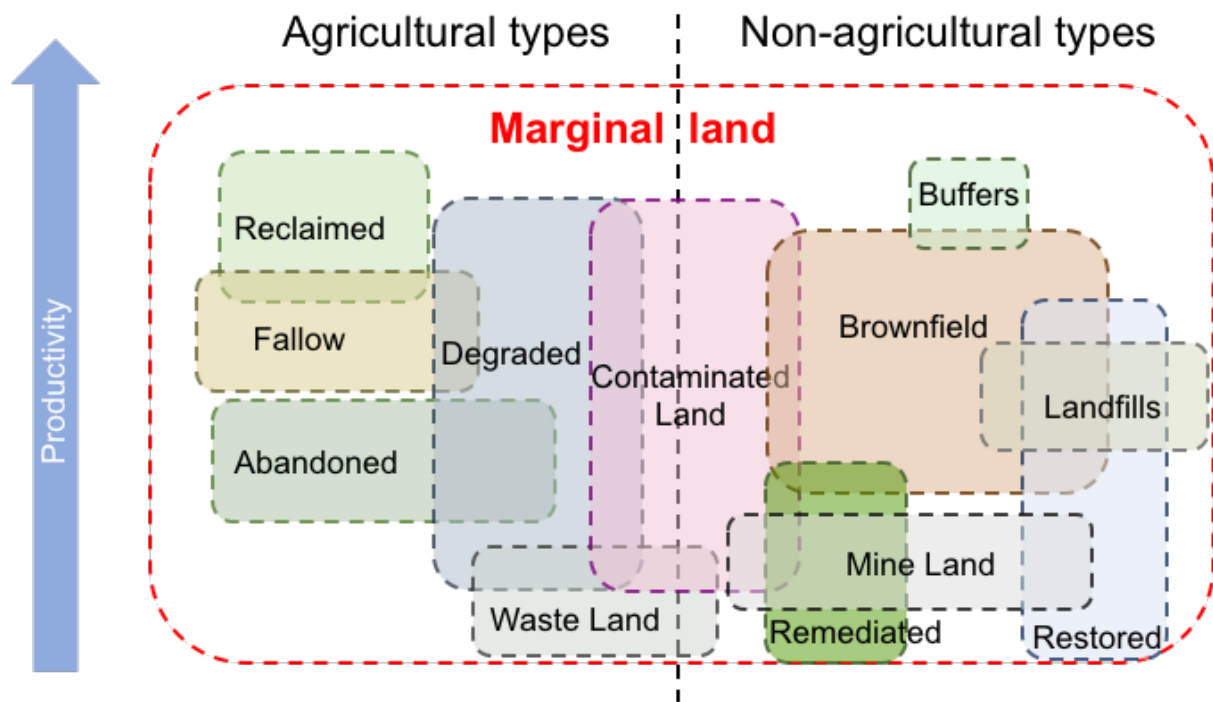
Regardless of the definition employed there are additional practical problems that have been discussed in the literature in relation to the use of marginal land for bioenergy production. At the forefront of these issues is the condition of land types being included as marginal land. The ‘law of marginality’ as described by Lal [83] states that marginal soils will produce marginal yields. Gelfand et al. [64] also highlight the problematic nature of identifying land with low fertility. The impact of selecting marginal land is quantified by Fischer et al. [84] who claim that yields are up to three times greater on suitable soils. Dauber et al. [40] add that often land is deemed marginal because of a lower yield potential based on a lack of precipitation, therefore utilising such land could result in a large water footprint. In addition to the issue of land quality, it has been argued that marginal lands are poorly located [64] and that the long distances needed to reach them could mean the loss of carbon dioxide neutrality of any energy produced [40]. These highlighted problems lead to doubts over the sustainability of marginal land for bioenergy crop production and, because of the umbrella nature of the terminology used, often several, vastly different, land types are considered to share the same limitations.

3.7 Redefining ‘marginal’ land to include non-agricultural types

To address these shortcomings and in the absence of a suitable alternative this paper proposes the following new working definition for future studies: “Marginal land is any identifiable land area, whether originally agricultural or non-agricultural, including those in urban areas, which is currently unused or underutilised due to economic, environmental or social factors, but which is suitable for temporary or longer term use for sustainable energy production”.

The schematic diagrams, of previous studies [29,40–42] can be adapted and combined as shown (Fig. 2) to aid use as a practical tool and taxonomy, highlighting the wide range of categories of land worthy of consideration. Non-agricultural and agricultural marginal lands are considered to be mutually exclusive and not readily transmutable, while accepting that both may be either contaminated or waste lands. Agricultural land is that which, was, is or could conceivably in the future be used for agriculture, which is in turn defined by the UK 1947 Agriculture Act [85]. Thus, the categories on the left-hand side of Fig. 2 can be considered as agricultural land resources, land that is currently, has been, or potentially could be, used for food production. It must be emphasised that low productivity areas not currently used for food production are included here as agricultural marginal lands (i.e. unused agricultural or other natural lands, including all natural waste lands), whereas these have been referred to as ‘non-agricultural’ by others (e.g. [11]). The various other types of naturally or agriculturally compromised soils or lands shown in Fig.1 (c) [42] (i.e. sandy, sloping, acid or saline soils, highly erodible land, drought-, compaction- or flood-prone soils) are not shown separately but would also fall within the agricultural part of the marginal land field of Fig. 2 and might overlap with waste land, abandoned or degraded types. The bulk of waste lands are included here with agricultural types, as these are areas that have naturally limited productivity due to physical and biological conditions [29], such as active dunes, salt flats, rocky outcrops, deserts, ice caps and arid mountain regions, but might conceivably become agriculturally productive in future [40]. In contrast, in this scheme only the categories on the right-hand side can be considered as truly non-agricultural land resources, land now rendered unsuitable for food production anthropogenically, or having a regulatory and/or protected status which prevents its use for food production. The diagram is designed to illustrate the possible overlap or exclusion between categories, so is topological, as the fields cannot also be drawn to scale.

Fig. 2. Proposed schematic diagram showing included land categories in terms of productivity and agricultural potential. The categories on the left-hand side can be considered agricultural land resources, land that is currently, has been, or potentially could be, used for food production.



4. Results & discussion

4.1 'Marginal' land studies which included non-agricultural land types

The extent to which non-agricultural land types are considered by previous research to contribute to the availability of marginal land was determined using the literature review. Some publications stick strictly to an economic-based understanding of marginal land, which leads to a focus on only marginal agricultural lands [54,60,69,86,87] or selection of lands only from an agricultural land classification dataset [23,70,88]. These studies make no attempt to include non-agricultural land types in their assessment of marginal land. Global scale studies deal with datasets at such a resolution that it is difficult to determine which land uses are included [28,89]. This is not intended to be a criticism of such global studies [49–52,71]. It is simply meant to highlight that it would not be possible to determine what proportion of the marginal land these studies identify is non-agricultural, based on their use of global land cover datasets. Additionally, the identification of degraded land, a term associated with marginal land related to a loss of productivity potential [90], has been attempted via a top-down assessment using the HYDE (History Database of the Global Environment) database [56]. This type of assessment, based on a historical global environment database, shares the limitation of producing an output from which it is challenging to distinguish identified land types, as well as further concerns that the degraded area identified may be in use or have a high biodiversity value [40]. Lastly, some studies seeking to identify marginal land based on land cover classification or physical and environmental characteristics simply fail to go into sufficient detail regarding the current use of lands identified [63,64].

These global scale studies, land degradation studies based on global datasets, and studies that fail to clarify the land use of identified areas were not considered any further in this assessment

of non-agricultural land inclusion in marginal land research. Furthermore, whilst abandoned agricultural land has been included as a marginal land type in some research [66,91], it was not considered to be a source of non-agricultural land in this review. This is due to the previously highlighted risk that idle farmland could come into use for agriculture in the future [40], therefore potentially causing indirect land use change if committed to bioenergy. Finally, considering the requirement to find a sustainable alternative to agricultural land, land types with the potential to have a high carbon stock or biodiversity value, such as shrubland or grasslands, were also not included as a suitable non-agricultural land resource, even if they were deemed to be marginal and not in use for food production. Turley et al. [92], for instance, include hedgerows and lowland bracken as an idle land resource but these were not included here. This stipulation led to the exclusion of further studies who seemingly only identified these highly vegetated or potentially bio-diverse land types [55].

After an evaluation of the marginal land literature 16 studies were found that explicitly include quantitative data for types of non-agricultural land and these are set out in Table 1. These studies were published between 2009 and 2018 and include eight studies conducted at a national scale, six at a regional scale and two at the local, or city, scale. Of these studies, nearly half consider land areas in emerging economies, albeit 6 were in China and one in India. The remainder are for all or part of three developed countries (USA, UK, Italy).

The definition of marginal land applied by each study varied. It should be borne in mind that these were each selected specifically because they had included the assessment of non-agricultural land types. Seven of the studies stipulated that marginal land must not be suitable for food-based agriculture [27,58,59,61,65,67,93]. However, a further four studies still specify marginal land as that which is not ‘currently’ available or not cost effective for agriculture [57,62,68,92]. Again, this raises the issue of the temporal nature of marginality. The different approaches taken often lead to plain contradictions. For instance, Gopalakrishnan et al. [27] include conservation land as a source of marginal agricultural land which contrasts with the definition of Niblick and Landis [93] that marginal land must not be ‘otherwise fulfilling conservation purposes’. Two of the studies, at the local or city scale, specified the inclusion of ‘urban marginal lands’ [65,94]. This led to the identification of various non-agricultural land types that may be found within the urban limits, such as vacant lots, land surrounding developed lots and underutilised areas. In contrast to this Milbrandt et al. [53] exclude all urban areas from their study. It is clear that a more consistent approach is required.

Beyond urban marginal land a wide spectrum of non-agricultural or other marginal land types has been considered. Most of the research conducted in China has included ‘barren’ and ‘bare land’, which includes shoal, bottomland, saline land, alkaline land [57–59,95] and, in one case, sand marsh and marsh land [61]. It is unclear how appropriate these land types would be for dedicated energy crop production, as in addition to poor biophysical conditions they may be inaccessible. One study in China [46] includes several additional non-agricultural land types, such as roadside land, stream side land, house surroundings and land risers or boundaries. This inclusion of buffer strips along infrastructure such as roads, rivers, rail, or canals has been mirrored in several other studies [27,53,62,92].

Table 1: Summary of areas of ‘marginal’ land found in studies that included non-agricultural land types.

Year	Author	Area	Scale*	Marginal Land Definition	Non-agricultural land types	Non-agricultural land area found (Mha)	Total marginal land area found (Mha)	Proportion of marginal land found that is non-agricultural (%)	Non-agricultural land as proportion of total land area (%)	Comments
2009	Gopalakrishnan et al [27]	Nebraska	M	Land not suitable for productive agriculture, which require inputs of water and nutrients to maintain productivity	River/riparian buffers; road buffers; brownfield sites	0.65	1.25	51.8	3.23	Brownfield deemed ‘insignificant’ and total includes conservation land
2010	Tang et al. [46]	China	L	Land that may be used for growing energy crops such as wasteland and paddy fallowed in winter, plus land risers, land boundaries and land along highways/roads	Wasteland, land riser/boundary, stream side land, house surroundings, land along highways/roads	55.65	110	50.6	5.8	
2010	Turley et al. [92]	England and Wales	M	Land where cost effective agricultural production is not possible under a given set of conditions	Land resources with no current agricultural value: roadside verges; railway embankments; canal margins; brownfield land	0.6	4.34	13.8	3.96	

2011	Zhuang et al. [57]	China	L	Relatively poor natural condition but is able to grow energy plants, or land currently not used for agricultural production	Barren land (shoal/bottomland, saline and alkaline land, and bare land)	5.21	130.34	4	0.54	
2012	Gopalakrishnan et al [62]	Nebraska	M	Land not capable of agroeconomic profitability based on land use, soil health and environmental degradation	Brownfield; riparian, road and impaired stream buffers; contaminated land	0.85	15.64	5.31	4.25	Lower range of estimates used for calculations
2012	Fahd et al. [68]	Campania	S	All non-cultivated areas where actual primary production is too low to allow competitive agriculture	Highly polluted land suitable neither for food production nor for biodiversity development	0.045	0.2	22.5	3.31	
2012	Liu et al. [59]	SW China	L	Land that has relatively poor natural condition but is able to grow energy plants, or land that is not currently in use for agriculture but is capable of growing certain plants	Barren land (shoal/bottomland, saline and alkaline land, and bare land)	0.007	0.92	0.77	0.005	

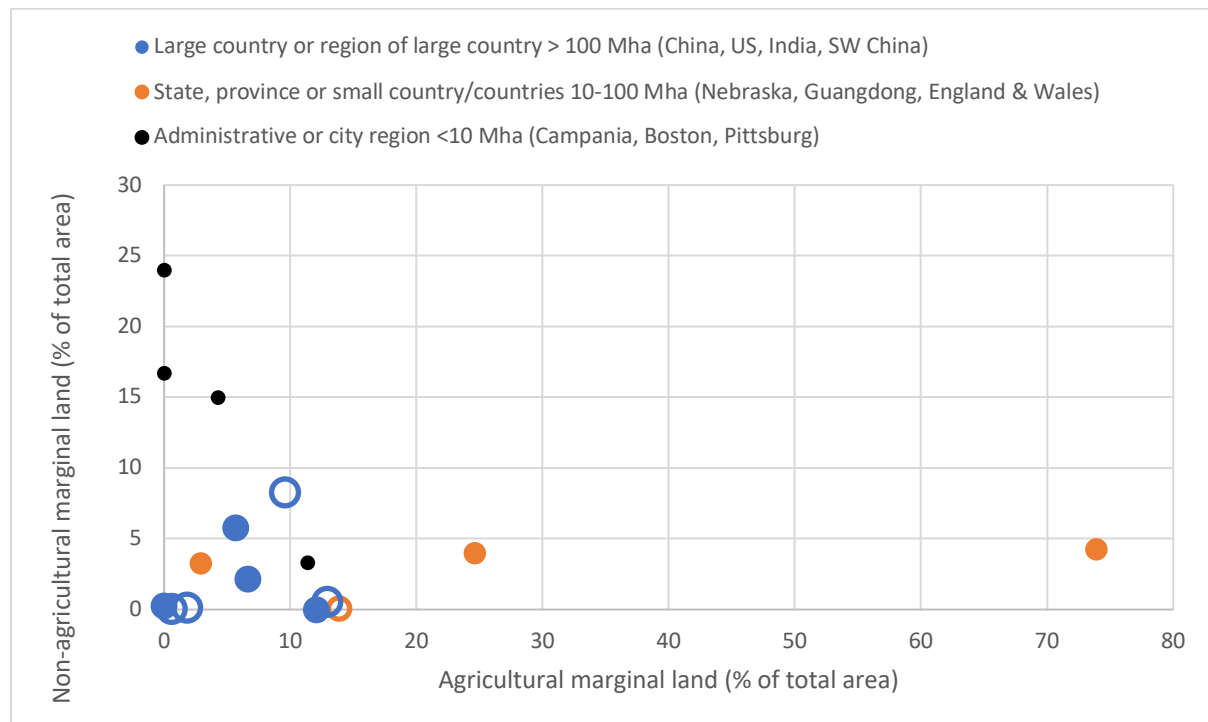
2012	Lu et al. [58]	China	L	Land unsuitable for crop production, but ideal for growth of energy plants with high stress resistance	Unused land (including alkaline land, bare land and shoal/bottomland)	0.86	18.28	4.7	0.09	
2013	Niblick et al. [94]	Pittsburgh US	S	Urban marginal lands: lots with poor agricultural potential and unfit for residential purposes	Vacant lots; surrounds of developed lots; special land uses: strip mines, gullied land, gravel pits, quarries, coal dump, industrial dump	0.002	0.002	100	16.7	Not clear what proportion of 2400 ha belongs to specific land types
2014	Milbrandt et al. [53]	United States	L	Lands with inherent disadvantages or lands that have been marginalized by natural and/ or artificial forces	Abandoned mine lands; EPA sites including brownfield and “Superfund” sites; Rights-of-Ways including road, rail and transmission line buffers; barren land	21.18	86.48	24.5	2.15	Excludes all urban areas
2015	Saha and Eckelman [65]	Boston	S	Urban marginal lands: land parcels that have limited economic value and are not suitable for agricultural purposes	Public/private lands; residential/ commercial underutilised areas	0.003	0.003	100	24	Not clear how ‘utilisation’ is measured i.e. backyards included
2015	Wang and Shi [61]	Guangdong Province	M	Land not suitable for growing field	Shoal/bottomland and unused land (sand marsh,	‘very small proportion’	2.5	n/a	n/a	

				crops due to edaphic and/ or climatic limitations, vulnerability to erosion, or other environmental risks, but might be usable for growing crops	marsh land, and bare land)					
2016	Edrisi and Abhilash [74]	India	L	‘Potential marginal land’ is defined as wastelands, all types of lands degraded by natural as well as anthropogenic activities, that meet a range of biophysical considerations	Mining/industrial wastelands	0.065	39.24	0.17	0.02	
2016	Niblick and Landis [93]	United States	L	Land unfit for food grade agriculture and not otherwise fulfilling conservation purposes or ecosystem services	Abandoned mine lands; brownfield land; closed landfill	2.82	2.82	100	0.29	
2016	Xue et al [95]	China	L	Land presently not used for agricultural production, residential purposes, and other social uses	Shoal land; bottomland; sand land; alkaline land; bare land	79.39	171.64	46.2	8.27	‘Suitable’ marginal land used for calculations rather than ‘available’ marginal land

2018	Saha and Eckelman [67]	MAPC region, Massachusetts	S	Lands that are not suitable for food based agriculture and have limited economic potential for fulfilling other ecosystem services	Residential and commercial underutilised areas; landfills; junkyards	0.053 – 0.071	0.071	75	15	Not clear what proportion is abandoned cropland of final 25% therefore lower bound used
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*Scale: S (small) <10 Mha, M (medium) 10-100 Mha, L (large) > 100 Mha

Fig. 3. Prevalence of marginal land areas comparing agricultural and non-agricultural types found in surveys at different scales (see Table 1). Open symbols denote studies including non-agricultural land types falling outside of our stricter definition.



In many of the studies non-agricultural land types are areas impacted by previous human use, whether contaminated land [62], former mining land [74,94], brownfield land [27,53,62,67,68,92,93] or landfill and dumps [67,93,94]. However, there is a stark lack of consistency as to which non-agricultural land types have been considered and, therefore, no standard methodology applied in order to identify these land categories.

The quantitative data for non-agricultural and agricultural marginal lands shown in Table 1 are summarized in Fig. 3. An extreme range of intensity of all marginal land is reported as a fraction of the total land area considered (0.3-78%). If the outlier in the former is ignored then the range seen for the intensity of agricultural (0-25, then 74%) and non-agricultural (0-24 %) marginal land types is broadly similar. Within these ranges the proportion of marginal land area categorised as non-agricultural also varies widely (0.017-100%). The three smallest scale, urban regional studies [65,67,94] found the highest intensities of non-agricultural marginal land overall (15- 24%) with almost no agricultural land types - as is to be expected given the tendency for these to be outwith city limits. Surprisingly, the remaining larger scale studies showed that the intensity of non-agricultural marginal lands often still approached that of agricultural types. However, it must be noted that some of these previous studies [57–59,61,95] included various natural marginal land types as non-agricultural which would be classed as agricultural marginal lands in our revised definition (see Table 1). The latter were all in China and included various natural wastelands in the totals for non-agricultural marginal land as these are regionally important. These are shown as open symbols to denote this ambiguity and possible overallocation of non-productive marginal land areas to the non-agricultural rather than the agricultural land totals.

The absence of conformity to a definition of marginal or the land categories that can be considered means that the actual areas of marginal land found and the relative contribution of agricultural and non-agricultural types should be treated with some degree of caution. What is clear from this critical review, however, is that consideration of non-agricultural lands types should not be overlooked when determining exactly what role marginal land could play with regards to bioenergy provision. Data was only available for all or part of three developed countries and two emerging economies. Clearly, more robust evidence is needed before any global policy decisions can be made to promote or discourage the use of this land type for bioenergy.

4.2 Opportunities for renewables provided by non-agricultural land types

This review has shown that overlooking non-agricultural land types is a critical omission in assessing marginal land resources, as this could risk ignoring up to half of the available land area at national scales, perhaps even more for urban regions. If the true potential of all marginal land for bioenergy is to be quantified then a better understanding of these land types is required, following an inclusive definition and exhaustive taxonomy with a clear analysis of any potential overlaps (Fig. 2). Each of the main non-agricultural marginal land types discussed in the literature is now considered in turn.

4.2.1 Brownfields

The definition of brownfield land varies globally, with a tendency in the United States to focus on the presence of contamination [96]. To distinguish it from other non-agricultural land resources that may be contaminated, the definition provided by Alker et al. [97] is that brownfield land is 'any land or premises which has previously been used or developed and is not currently fully in use, although it may be partially occupied or utilised. It may also be vacant, derelict, or contaminated' [97]. Brownfield lands are often considered eyesores or even potential health hazards [98]. The difficulty of redeveloping these sites, coupled with the increased requirement for renewable sources of energy have resulted in them being considered for renewable energy provision [98]. In terms of biomass production, brownfield land has been investigated as a potentially usable land resource in the North East of England with a scoping study of available non-agricultural land types [99,100]. The practicality of utilising this land type for bioenergy production has been evaluated by several further studies. Lord [43] describes the use of compost to establish energy crops on brownfield land, offering longer-term soil carbon benefits [45] and productivity within the range 4-10 dry t.ha⁻¹a⁻¹ postulated for uncultivated lands with "marginal potential" [11]. Furthermore, Smith et al. [101] compared the yield of bioenergy crops on a remediated site in the United States with a historically cropped agricultural site and found there to be little difference in yields, arguing that brownfield land has the potential to produce suitable quality feedstock.

Brownfield land has also been assessed in terms of the role it could play in providing other renewable energies. Adelaja et al. [98] investigated the wind and solar potential on brownfield sites in Michigan, concluding that utilisation of this resource could provide 43% of Michigan's residential electricity consumption. Similarly, the potential for brownfield redevelopment for solar energy purposes has also been investigated in the Czech Republic [102]. In the UK, Donaldson and Lord [103] have provided an assessment of the brownfield land availability in Glasgow City, arguing that these sites could be reused for ground source heating to help alleviate fuel poverty in the city. In the United States research regarding brownfield land for

renewable energy provision is often undertaken alongside the consideration of other contaminated land types. Foremost of these attempts is the Environmental Protection Agency's 'RE-Powering America's Land' initiative, which sought to better understand the role formerly contaminated lands, landfills, and mine lands could play for renewable energy development [104]. This initiative includes brownfields as well as "Superfund" sites, sites contaminated by hazardous waste and identified by the EPA for clean-up as contaminated lands. Mosey et al. [105] investigated these 'limbo lands' on behalf of the EPA, creating a screening process to identify sites with a high potential for renewable energy technologies. More recently, Waite [106] undertook research regarding the potential for renewable energy installations on 81,000 sites associated with federal clean-up programs in US.

4.2.2 Landfills

Both Mosey et al. [105] and Waite [106] in America, and Evans [99] in the UK, have included landfill as an option for siting of renewable energy technologies. McKendry [107] has discussed the potential for restored landfill sites to provide biomass which could supplement landfill gas fuelled power stations. Furthermore, Ettala [108] studied tree plantations on six landfill sites in Finland, finding that short-rotation plantations can be established and the quality of the resulting biomass would allow it to be cultivated as a source of energy. The concept of using closed landfill for the provision of renewable energy has also been investigated in Hungary [109], with researchers declaring solar photovoltaic installations on former landfill sites a 'win-win'. According to their findings the establishment of solar PV systems can simultaneously avoid the environmental, economic and land value concerns of post landfill closure whilst providing renewable energy.

4.2.3 Mine lands

Another land type also considered by the EPA Re-Powering America initiative [104] is abandoned mine land. In reference to the EPA initiative, Buchsbaum [110] argues that abandoned mines and the area immediately surrounding them are not usually considered for reuse due to safety and environmental concerns, yet there have been examples of them being utilised for cleaner sources of energy in countries such as Germany [110]. This has also been discussed elsewhere, with Rocio [111] even suggesting that an abandoned mercury mine could be cropped. A Waste & Resources Action Programme (WRAP) project identified the potential for biofuel crop production on a restored former coal washing site in Kinglassie, Scotland [112]. Old mineral workings have also been considered in terms of their potential for siting bioenergy projects [113], with Dubuc [113] identifying clusters of quarries that be used for energy crops to satisfy nearby power plant demand.

4.2.4 Contaminated, remediated and restored land

There is the potential for soil contamination to be present in brownfields, landfills and mine lands. Surveys indicate the existence of 2.8 million potentially contaminated sites, just across the EU-28. While 650,000 sites have been registered, only 1in10 have so far been remediated [114]. The main activities responsible are waste disposal & treatment, followed by industrial & commercial activities, while the main types of contaminants are potentially toxic elements (including heavy metals) at roughly a third of sites, followed by petroleum at nearly a quarter [115]. Together with poly-aromatic hydrocarbons, other aromatic hydrocarbons and chlorinated hydrocarbons, organic compounds together account for over 50% of all

contamination. The management of EU contaminated sites is estimated at €6 billion annually [116]. The extent of land area affected by contamination is more difficult to define or quantify. Agricultural lands may also be contaminated naturally, from industrial pollution or after agricultural spreading. For example, a 2014 Government study in China found 16.1% of all soil and 19.4% of arable land showed contamination, with Cd, Ni and As the main pollutants [117].

To acknowledge their potential distribution, contaminated lands are shown spanning both agricultural and non-agricultural marginal lands (Fig. 2). It is now well established by successful demonstrations that remediated and restored sites may offer an opportunity for biomass production, whether these were originally brownfields [100,118], landfills [101,119] or mining sites [120,121]. A number of studies suggest that combining phytoremediation with energy crops is a “win-win” opportunity [18,122–124]. Here remediation is the remedying of issues such as soil contamination or dereliction, whereas restoration refers to reinstatement of land, especially after mining or quarrying excavation or landfilling of waste deposits. These generalisations are reflected in the complex overlapping fields shown for these inter-related types of non-agricultural marginal land.

4.2.5 Buffers, utility & urban lands

Riparian buffers were included in the assessment of marginal land undertaken by Gopalakrishnan et al. [27,62]. Areas surrounding waterways have been investigated by Fortier et al. [125] who assessed the potential to produce biomass on deforested farm streams in 3 watersheds. Various unconventional urban sources of non-agricultural land have been considered for renewable energy technology establishment [126]. Arodudu et al. [126] employed a GIS methodology to identify and estimate the bioenergy potential from green roofs and construction sites which the authors argue could be used in addition to domestic organic waste and leaf-fall collection from recreational parks. Van Meerbeek et al. [127] also suggest that residues could be collected from a range of non-agricultural ‘landscape biomass’ sources such as sports fields, parks, roadsides and conservation areas.

4.3 Challenges to identify or classify non-agricultural lands

A common theme and limitation raised across these studies again is the quality of data and consequently poor methodologies employed. Oliver [96] outlines the requirement for more data regarding brownfield in Europe to enable successful monitoring of flows in this resource. The presence of incomplete or missing data has also been highlighted [102]. This requirement potentially undermines the validity of these studies as a representation of the land resource that exists. Mosey et al. [105] considered the provision of ‘limbo lands’, including landfill, “Superfund”, abandoned mine land, brownfield and former industrial sites, and yet the analysis only utilises data from the National Priorities List of sites ‘threatening releases of hazardous substances, pollutant or contaminants’ [105]. Likewise, Waite [106] is limited to the sites that had been screened by the EPA’s initiative, and the author admits that only eleven states provided further data. Additionally, the studies that implement a GIS approach to identify brownfield land, such as Niblick and Landis [93], have represented the land parcels as points, yet if any judgement is to be made about their suitability for siting renewable technology further detail on their layout would be required. One attempt to create a more detailed picture of the collective non-agricultural land resource, is the investigation undertaken in North West

England as part of the Newlands Project (New Environments via Woodlands) [128][129][130]. This implemented a bottom-up approach based on aerial imagery and desk studies to identifying any derelict, underused and neglected land parcels, then consulted local authorities regarding the identified sites and evaluated end-use suitability while recording potential socio-economic benefits. Future attempts to identify the non-agricultural land resource for renewable energy provision could consider adopting elements of this methodology to gain a better picture of the collective land resource and cost-benefit analysis.

4.4 Using non-agricultural land types - Benefits

Considering non-agricultural land separately from other marginal land allows the unique benefits of using these land types to be fully captured. Spiess and De Sousa [131] summarise the advantages of siting renewable energy technology on brownfield land as ‘triple bottom-line benefits’, with environmental, social and economic gains. The most notable of the triad of benefits is the reduced environmental impact of using these land types, either for bioenergy or other renewable technologies. Most relevant is the unique opportunity that using land types such as brownfield land could provide in producing carbon neutral biomass without impacting on food production [132].

It has been argued that implementation of bioenergy could bring a range of further environmental benefits such as ecological improvement [132], blight removal [98], and helping to rebuild the soil profile on land that is often of poor quality [42]. Blanco-Canqui [42] has even suggested that growing dedicated energy crops on reclaimed mine soils can have a higher potential to sequester soil carbon in the first 20-25 years following reclamation than on agricultural land. Lord and Sakrabani have shown that significant soil carbon increases extend beyond 10 years when compost is used to establish perennial energy crops on brownfields [45].

As has already been suggested a further benefit from bioenergy production on contaminated lands is the role these energy crops could play in remediating the sites [18,132]. Phytoremediation is the use of plants to destroy, extract, stabilize or contain contaminants [18], and has been promoted as a cost effective *in situ* remediation option [42] that avoids the need for energy intensive process-based remediation or extraction [132]. Phytoremediation has also been encouraged, despite being a slower form of remediation [133], due to the additional environmental advantages of erosion control, reduced greenhouse gas emissions and waste generation, and increasing the biodiversity on sites [18], whilst simultaneously generating revenue from the biomass sold [134]. Many contaminated sites currently have a negative asset value due to the anticipated costs of future remediation or maintenance [132] which could be side-stepped if the site is put into use for bioenergy provision. Alternatively, other sites are not contaminated enough to trigger regulatory remediation options and therefore sit idle and derelict [18], which could be avoided if these sites were considered as a source of bioenergy. In the case of landfills, phyto-capping, the placing of a layer of soil material atop the landfill and growing of a dense layer of vegetation, has been deemed to enhance aesthetic qualities and introduce economic benefits if energy can be generated [135]. Lamb et al. [136] describe how phyto-capping can also mitigate the environmental impact of leachate generation and GHG emissions. Finally, a further set of unique environmental benefits have been claimed if renewable energy technologies target the urban non-agricultural land resource - including the role that biomass could play in urban flood prevention, reducing the urban heat island effect [126] and delivering other ecosystem services [42].

It has also been argued that there are economic benefits to be gained from using non-agricultural land for bioenergy provision [120]. One such economic benefit, which can be extended to other land-based renewables, is that reusing these non-agricultural land types may be more cost effective as they already have road connections, and often also have fencing and are connected to the grid [109,131]. Furthermore, Donaldson and Lord [103] argue that brownfield land can provide low cost energy to target fuel poverty, identifying a tendency for these sites to be in close proximity to social housing in urban areas. It has also been claimed that targeting brownfield land for bioenergy can lead to the creation of jobs and investments in often run-down post-industrial landscapes [98,131].

Utilisation of non-agricultural land types can give other positive social impacts. Using sites for bioenergy provision, for instance, has been linked to community redevelopment benefits [98,132] and aesthetic improvement [120]. Bambra et al. [137] have called for brownfield land to be considered an element of environmental deprivation, highlighting the link between brownfield land and spatial inequalities in health, including morbidity. This research concludes that people living in wards with a higher proportion of brownfield land are significantly more likely to suffer from poorer health than those living in wards with less [137]. The paper not only links contaminated brownfield with potential risks to physical health via the 'source-pathway-receptor' model, but also argues that brownfield land is an 'untherapeutic landscape' [137] and a marker of long term industrial decline and 'spoiled identity' [137]. The authors contrast the state of brownfields with the notion of biophilia, arguing that humans prefer natural settings due to an inherent association with resources and protection [138]. From this perspective, the greening or remediation of brownfield or other non-agricultural land types could be considered to have wider societal benefits and could potentially be linked to an improvement in community health.

4.5 Using non-agricultural land types - Challenges

The most prominent issue for the use non-agricultural land types for renewable energy deployment, particularly bioenergy, is the quality of the land. Lord et al. [132] outline several challenges that may face attempts to grow biomass on these land resources including shallow soil depth, compaction and low water retention, limited nutrients, low organic matter and potential phytotoxicity [43]. Additional issues arise due to competition on these sites from weeds and pests, and the existence of structural remains and made-ground [43]. The quality of the land can have a direct impact on the ability to grow biomass productively on these sites and Blanco-Canqui [42] concludes that a lower yield is to be expected compared with prime agricultural land. Spiess and De Sousa [131] consider that the main difference between renewable energy developments on brownfield land and other sites, is in the potential for contamination, eclipsing the various other technical, environmental, financial, regulatory, industrial, and social barriers discussed below. Donaldson and Lord [103] reiterate this point, emphasizing that the additional costs associated with remediation need to be considered if non-agricultural land types are to be utilised for renewable energy technologies.

In common with all marginal lands, primary productivity will be controlled by other biophysical factors, including insolation, rainfall and climate, which may be severely reduced in less desirable agricultural areas [11], or by environmental restrictions for unused areas of higher productivity land, such as the requirements of the EU Renewable Energy Directive's sustainability criteria [139,140]. Furthermore, any theoretical land area or bioenergy resource

will be substantially reduced when realistic availability, technical or economic factors are considered [141,142].

Besides the challenges associated with land quality further complications can arise due to the high proportion of these land types within, or close to, urban areas [67]. The urban setting can lead to access and logistical problems or potential developers being faced with high land prices and labour costs [67]. The siting of renewable energy technologies can also lead to neighbourhood concerns [67] and an element of NIMBYism [131].

According to Saha and Eckelman [67] a further barrier to deployment of renewables in urban areas, is the competition for use of the land with other economic activities. This is not unique to urban areas as there is a wide spectrum of potential end uses for non-agricultural land resources that are currently left idle or underutilised. Current work has focused on the wider benefits, other than via development, of urban brownfield land [143], which has the greatest competition for use, given the barriers to using land types such as closed landfill and abandoned mine land. Of these, their potential use for ecological restoration is most common [143–145]. There has been an increased awareness of the importance of previously developed land for wildlife [145] and biodiversity conservation [144]. Macadam and Bairner [145] argue that brownfield sites can support many rare, scarce and UK Biodiversity Action Plan [146] priority species. Similarly, Plieninger and Gaertner [144] have suggested that degraded lands may support biodiversity levels similar to or above those of managed landscapes and are therefore an untapped resource for conservation [144]. They argue that use of these lands for bioenergy may generate difficult trade-offs with ecosystem functions and conservation of biodiversity, even claiming that energy crops exhibit ‘traits of invasive weeds’ [144]. It has been suggested that these non-agricultural land types, such as brownfield land, would be better utilised as a source of greenspace, including wildflower meadows [147] or forestry [148]. Mathey et al. [149] has proposed that brownfield land in urban settings would be ideal for greenspace provision with the additional benefits of microclimate regulation and new recreational space development. In contrast, it has also been suggested that brownfield land could play an important role in housing provision [150]. A report produced by the Campaign to Protect Rural England, concluded that up to 1.1 Million homes could be built in England on brownfield land, with enough land to meet 5-year house land supply targets [150]. In summary, competing uses could be a barrier for the implementation of bioenergy developments, or other renewable technologies on the land, highlighting the requirement for detailed, usable information on this land resource to guide future decision making.

4.6 Implications for future work

To improve future estimates of the specific contribution that different non-agricultural or marginal land types could make to renewable energy provision, better quality site data and a more consistent identification methodology are needed. A consistent and inclusive definition and classification scheme, such as those proposed here (Fig. 2), are prerequisites for consistent identification, accurate classification and quantification of the resultant bioenergy potential. Any future attempts should consider taking a bottom-up approach [30] in order to gain a more detailed understanding of their spatial properties and distribution. A more detailed representation of these land resources will ultimately enable a more accurate assessment to ensure that land can be mobilized for the most appropriate end usage, whether that be as a source of sustainable bioenergy, or for an alternative competing use, such as greenspace or

housing provision. Furthermore, a combination of a detailed understanding of the non-agricultural land resources that is available for second generation biomass crops could be combined with other relevant datasets, such as the availability of non-conventional urban sources of biomass [126] or the residue that could be accrued from landscape biomass [127], so as to provide a unique national assessment of the provision of bioenergy that could be achieved without impacting on agricultural production. Critical selection criteria for implementation will be the unsuitability, unacceptability or unavailability of these sites for future food production, coupled with adequate biophysical conditions for socio-economically viable production, while still meeting acceptable environmental and other sustainability criteria, including the UN Sustainable Development Goals [151].

6. Conclusion

This paper has clearly demonstrated that there are many remaining issues with the potential of marginal land to support sustainable biofuel production. The current discourse is dominated by discussion of the role that such alternative land resources could play if not in use for food production. This qualitative review has highlighted several recurring problems. Critically, the ambiguity in previous definitions of marginal land and the associated lack of any consistent identification methodology reduces the level of confidence that can be attached to any subsequent results. Furthermore, the temporality of the economic definition often employed leads to concerns regarding the longevity or sustainability of the land identified as being marginal or whether it might be needed for future food production. The new definition proposed directly addresses this temporality issue and encompasses a wider range of non-agricultural sites manifestly unsuitable for food production, illustrated in a comprehensive schematic diagram (Fig. 2).

Quantitative evaluation of the literature has highlighted the variable inclusion of non-agricultural land types within marginal land resource assessments. The past studies are compromised by inconsistent definitions, methodologies and inclusion of different non-agricultural land categories. However, non-agricultural marginal lands can be as much as a quarter of the land area considered and may contribute up to half of the total identified marginal land areas, even at country scale.

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