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Geospatial assessment of potential bioenergy crop production on urban marginal land

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HIGHLIGHTS

- A GIS-based tool was developed to assess urban marginal land and bioenergy yield.
- An area of 2660 ha of land was identified, representing 24% of total urban extent.
- The potential bioenergy yield is 830 TJ for poplar if 100% marginal land used.
- Urban bioenergy systems have potential economic and environmental co-benefits.

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ABSTRACT

Urban marginal land can be used for growing high yield bioenergy crops such as miscanthus and poplar. Here, a GIS-based modeling framework was created to assess potential urban marginal lands in Boston that include vacant lands and under-utilized public and private areas with adequate soil quality and sunlight. Using ArcGIS model builder as a spatial analysis tool, land parcels were screened for typical urban features such as buildings, driveways, parking lots, water and protected areas. The resultant layer was subjected to bio-geophysical modeling that includes soil quality, slope analysis and finally shadow analysis. Approximately 2660 ha of potential marginal land was identified as suitable, representing 24% of total land area in Boston. Using crop yield information, it was estimated that this marginal land could be used to produce up to a total of nearly 42,130 tons of high yield short rotation poplar biomass in a regular growing season. Also, bioenergy potential calculation revealed that for short rotation poplar, this amount of biomass can potentially yield up to 745 TJ (LHV) to 830 (HHV) TJ of yearly primary energy for the city of Boston that can be used for heat or electricity production, particularly for microgrid or district heating applications. This is equivalent to ~0.6% of Massachusetts primary energy demand for 2012. Ongoing work will explore other urban regions of Massachusetts and the Eastern US that might be able to fulfill part of their energy demand locally while providing benefits in environmental quality, economic development, and urban resilience.

1. Introduction

Urban inhabitants represent the majority of global energy demand (75%), with more than 50% of the population currently residing and working in cities [1]. Although densely settled cities cannot be self-sufficient in food or energy production, many communities are considering growing dedicated energy crops on under-utilized land to produce food and fuel for district heating and small-scale electricity production [2]. Such schemes provide opportunities for public and private actors in municipalities to fulfill part of their energy demand locally while providing potential benefits to residents in the form of improved landscapes, economic development, and modulation of urban heat islands [3]. Local sources of energy may provide a temporary buffer to communities when a power grid failure or heating fuel supply disruption occurs due to natural catastrophes such as hurricanes and floods [4]. However, it is important that urban bioenergy production address community concerns such as odor, noise, or increased traffic [5], and not impede other beneficial uses of valuable urban land.

A study conducted by U.S. Department of Energy reported an increase of bioenergy production by more than 300% in the past decade, with potential 1.9 PW h available annually in the contiguous United States [6,7]. While much of the recent increase is due to corn ethanol, woody biomass has seen growth as a primary or secondary fuel in electric generating units and in residential high-

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efficiency pellet stoves. In addition to large-scale agricultural and forestry operations to supply this bioenergy, urban marginal land can also play a part in larger bioenergy production systems. Previous studies have characterized urban marginal lands as land parcels that have limited economic value and not suitable for agricultural or residential purposes [5,8]. A central challenge of this work is to determine the extent of marginal land for urban regions [9]. Recent urban energy and geography research has focused on the development of computational tools to acquire data and estimate urban marginal land for different cities [10]. One study estimated that approximately 15% of U.S. urban land on average can be considered marginal [11]. Recently, many cities have been reclaiming their marginal or under-utilized land parcels for use as recreational parks, playgrounds, and community gardens. However, growing dedicated energy crops on these urban lands is a fairly new concept and needs further investigation, even just to understand the scale of potential energy benefits.

Marginal land estimations for the U.S. have been conducted nationally, regionally and at the city scale (Table 1). Scale and location are critical issues, as it is not cost-effective to transport biomass resources over long distances [10]. Limited agreement exists among techniques used to estimate potential for bioenergy schemes in previous studies [1,12–14], but common approaches make use of Geographic Information System (GIS) and remote sensing based tools [9]. GIS-based tools assess spatial patterns of biomass based bioenergy production on marginal land for both urban and non-urban areas as well as availability of suitable land.

Milbrandt et al. [18] looked at national level for estimating biomass based bioenergy resources. The study reported 8.6 million km^2 of marginal land availability in contiguous U.S., which is equivalent to 8.5% of total land area. They considered non-urban abandoned lands, brownfield and transportation right-of-ways for marginal land estimation and herbaceous crops (switch grass and miscanthus) as biomass feedstock. At the regional level, Gelfand et al. and Gopalakrishnan et al. [15,16] conducted assessment for the US Midwest and Northeast, respectively, considering lignocellulosic biofuel based bio-energy production system in primarily non-urban regions. At these scales, an important benefit of using marginal land is that it does not diminish agricultural production and use of prime farmlands and therefore can avoid ensuing impacts due to indirect land use change [19].

At local or municipal scales, several studies have conducted detailed mapping of marginal land availability through parcel-level screening of land use and soil quality [4,17,20–23]. Typically these local scale studies assessed bioenergy availability in meeting urban or regional renewable portfolio standards, or as a question of urban self-reliance. Proper quantification and geolocation of practically usable marginal land is critical to the successful planning of urban bioenergy systems. Unlike regional or national level studies, local scale studies are capable of incorporating parcel-level ownership and assessment records, road and riparian boundaries, and socio-economic considerations that are relevant for municipal authorities. Niblick et al. [17] incorporated several of these aspects in an urban land study for Pittsburgh, PA, finding 35% of the city as marginal lands of limited economic value that could be sustainably cultivated for sunflower based biofuel production. Metal uptake was also considered in a subsequent study, as urban vacant lots frequently have contaminated soils [24]. Finally, Grewal and Grewal [4] investigated Cleveland, OH as a test case and assessed vacant lands equivalent to 40% of that city's total land area that could be suitably used to develop high-yield algae based biodiesel production scheme.

Here we built on previous work for the assessment the marginal land and bioenergy potential at urban scales, using Boston, MA, USA as a case city. Additional attribute-based and geospatial modeling tools were employed, and, to our knowledge, this is the first urban-scale study to conduct a detailed parcel-level screening of layers for public and private ownership, zoning, parcel size, slope, soil quality and shadow analysis. Both herbaceous (miscanthus) and woody based (poplar and willow) energy crops were considered for biomass and bioenergy yield estimation. These are believed to be the best yielding fast-growing species in the Northeast U.S. [20]. Each has been shown to have a positive net energy balance and can be effective in both fulfilling energy demand and mitigating climate change [12]. The outcome of the study looks to provide policy makers and bio-energy developers with a better understanding of the scale of urban bioenergy opportunities, while also contributing to the larger research question of urban energy self-sufficiency.

2. Methods

Estimation of potential bioenergy yield from urban marginal land for Boston was performed in several steps, represented in Fig. 1. A GIS-based site suitability analysis was performed using ArcMap 10.3 (ESRI, Redlands, CA). Land parcel layer was used as an input into GIS model and series of linear combinations of spatially referenced layers were used as screening layer with some boundary conditions to identify land parcels that can be suitably used. Here urban marginal land was defined as land that is not suitable for primary agriculture, has a soil slope <15% and has a minimum parcel size. Land features that fit these criteria can be diverse especially within built up areas. For Boston, these included (but may not be limited to) public and private vacant lands, residential and commercial under-utilized areas, and degraded lands and fill. Finally, total biomass and bioenergy potential was calculated using estimated urban marginal land, energy crop yield information, and heat content. The input data sources, estimation approaches, and validation techniques are explained in detail below for each step.

2.1. Land use type screening

First, potential marginal land areas were identified using GIS site suitability model developed for screening purposes (Fig. 1). This model consists of an input layer, erase layers and the output suitable parcel layer (Table 2). The input layer was a 2013 record of all City of Boston parcels. Several screening layers were joined and overlaid with the input layer to exclude areas unsuitable for biomass cultivation because of existing improvements or zoning restrictions. These screening layers included area occupied by buildings, driving lots, parkways, protected areas (parks and recre-

Table 1
Review of studies on marginal land assessment in the USA.

Year	Author	Scale (USA)	Crop	Marginal land definition	Percentage of total area
2011	Gopalakrishnan et al. [15]	Regional (Northeast)	Lignocellulosic	Contaminated brownfield	8.0
2013	Gelfand et al. [16]	Regional (Midwest)	Cellulosic	Crop land with low soil quality	10
2013	Grewal and Grewal [4]	Local (Cleveland, OH)	Algae	Vacant lands	40
2013	Niblick et al. [17]	Local (Pittsburgh, PA)	Sunflower	Vacant and abundant lands	35
2014	Milbrandt et al. [18]	National	Lignocellulosic	Abandoned lands, brownfield, right-of-ways	8.5