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Geospatial mapping of biomass supply and demand for household energy management in Nepal

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ABSTRACT

This paper presents a geospatial mapping model for assessing spatial distribution and demand of biomass sources for household energy use in Nepal. In the context of rural households, correlation between supply and demand of biomass is crucial for designing effective rural energy programs. Three districts were considered to represent the country's main topographical regions: lowlands, hills, and mountains, where geospatial distribution and demand of biomass are different. The supply potential of fuelwood was assessed using Geographical Information System (GIS) tool, and the potential of crop residues and dung and household energy demands were determined by field surveys and experiments. The results showed that households with secure access to biomass sources in lowlands, hills and mountains were 57%, 50% and 3% respectively. In lowlands, crop residues and dung were extensively used due to lack of forest biomass, whereas forest biomass was extensively used in hills and mountains, with negligible use of crop residues and animal dung. The results indicate that use of improved cooking stoves and biogas was negligible and thus cleaner biomass energy conversion and cooking technologies are needed to achieve universal target of clean cooking for all. The GIS model provided better estimation of biomass energy supply potential in the communities, which is crucial in the design of energy policies for sustainable clean cooking solutions. It is anticipated that this geospatial mapping model is also applicable to the cases of other developing countries, which have dominant biomass consumption for household energy use.

1. Introduction

Biomass shares a significant portion of household energy use in the developing countries (Saygin et al., 2015; Cantarero, 2020; Kindermann et al., 2008). Under the framework of sustainable development goal 2030, biomass is an important energy source to support the clean energy generation target of the United Nations (Saygin et al., 2015; Thofern, 2011; Iverson et al., 1994; Vávrová et al., 2017). As biomass is used mostly as a traditional fuel in developing countries, there is a lack of scientific information on biomass sources and their spatial distribution, which has hindered the development of new technologies and appropriate policies for supply and demand management of household energy (Long et al., 2013; Rosillo-Calle et al., 2015; Ullah et al., 2015). The Geographic Information System (GIS) has been used as an appropriate computational tool to calculate the comprehensive spatial distribution of biomass resources (Kindermann et al., 2008; Iverson et al., 1994; Vávrová et al., 2017; Băneş et al., 2010). The technical potential of biomass energy could be estimated by considering distance, means of

transportation, and relevant landscape details in GIS (Băneş et al., 2010; Milbrandt and Overend, 2008; Van Hoesen and Letendre, 2010; Chauhan, 2010). The modeling of energy resources in GIS provides spatial distribution, which is crucial to develop future energy technologies and systems. The GIS method helps to create useful maps with spatial distribution of different biomass resources and compare different energy options, and environmental and economic constraints. In this paper, we have presented a model for spatial mapping of biomass sources: fuelwood, crop residues, and animal dung considering the case of Nepal.

Nepal relies heavily on biomass fuels to meet its energy needs, which contributes about 85% of the total energy use (about 77 million barrels of oil equivalent). The residential sector consumes about 90% of this biomass energy for cooking and space heating. The fuelwood, agricultural residues, and livestock dung are the sources of biomass with contributions of 88%, 5% and 7% respectively (WECS, 2014). Among three major geographically different regions of the country, the hills and mountains have relatively good forest resources as compared to lowlands (Chakraborty, 2001; Gautam et al., 2004; FAO, 1999; WECS,

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2010). In lowlands, crop residues and animal dung are extensively used for households energy needs due to deficit of fuelwood, whereas such uses are quite limited in other two regions (WECS, 2010; Pokharel and Chandrashekar, 1994; Pokharel, 2004; Pant, 2013). Direct burning of biomass has caused significant indoor air pollution, damage of forest ecology, and agricultural productivity (Pant, 2013; AEPC, 2014; AEPC, 2010; Singh et al., 2012; Metz, 1991; Melsom et al., 2001; Kurmi et al., 2013; Devakumar et al., 2014; Gami et al., 2009; Upadhyay et al., 2005). Over the past few decades, the government and various international agencies have initiated some programs to provide clean energy sources for cooking and reduce biomass consumption, mainly the dissemination of biogas and improved cooking stoves (ICS) with different types of subsidies (Gami et al., 2009; Upadhyay et al., 2005). The dissemination of biogas technologies can play a significant role in reducing traditional biomass use but presently, it is used by less than 3% of households. Improved cooking stoves (ICS) are used by a similarly low percentage of households (AEPC, 2015). These results indicate that the household energy use is highly inefficient as they mostly rely on traditional biomass burning. The health impact is severe to inhabitants, especially during cooking hours due to high indoor emissions of CO₂ from inefficient burning of biomass in non-ventilated buildings (Pokharel and Rijal, 2020). Furthermore, the use of ICS and biogas is negligible although they are more efficient and cleaner than traditional biomass burning. Hence, for the long run, the evaluation of sustainable biomass supply potential for cleaner energy production is the key step for long term energy planning based on which the need of intervention of other energy technologies can be explored. Given the need of technological intervention for utilizing biomass as clean fuels, biomass mapping would provide important information.

In Nepal, about 50% people live in the lowlands, followed by 43% in the hills and 7% in the mountainous regions (CBS, 2011). In mountainous regions, fuelwood is the main energy source for almost all households, whereas this share is about 67% in hills and 57% in lowlands (CBS, 2011). In lowlands, the households use other fuel types such as dung cake, liquefied petroleum gas (LPG), kerosene and biogas. About 22% of these households burn dung cake in lowlands, whereas no such households exist in the other two regions. The fuelwood utilization is more in rural households than in urban, whereas the monthly national average use of fuelwood is higher than that of other developing countries (Shahi et al., 2020). Even though crop residues are used for cooking and space heating especially in lowlands, this information is not incorporated in national energy statistics. As such, other sources such as electricity, waste, coal, briquettes, etc are marked as "others". Furthermore, there are no specific building designs that incorporate space heating in households. About 22% households have concrete walls, 29% have cement-bonded stone walls, and the remaining have walls made from local materials such as thatch, straw, wood, and mud (CBS, 2011). Due to direct burning of biomass with improper ventilation and lack of designs for space heating and cooling, heat is wasted in winter whereas excessive heating takes place in summer (Pokharel et al., 2020).

National biomass energy strategy of Nepal revealed that local biomass could not be deployed effectively for energy generation because of inadequacy of resource information (MoPE, 2017). Biomass assessment is the key to manage sustainable biomass supply for various alternative uses including energy generation in a society which also provides an opportunity to promote local bio-economy (Hoang et al., 2020). The current energy policies and programs are based mostly on households' demand due to self-awareness created by various community-level organizations, governmental institutions, non-governmental agencies, and private energy companies (AEPC, 2016). In some cases, various government and non-government agencies have directly intervened improved cooking stoves to poor and socially-excluded households through subsidies and incentives (REDP, 2009; SNV, 2013). Due to lack of reliable information on biomass sources, there are challenges in designing appropriate programs for rural households.

Availability, accessibility and calorific value of biomass energy sources are the key aspects that determine the actual potential for energy generation. This is important, particularly for Nepal where the country's topographical variations impact the distribution of forest biomass to determine the availability and utilization sources. Geospatial mapping of biomass is important because the collectable biomass is influenced by many factors such as, distance between the sources and the end-use locations, the extent of resource-protected areas, transportability and corresponding economic aspects. These parameters can be modeled in GIS to determine the spatial distribution of biomass sources (Long et al., 2013; Yousefi et al., 2017; Fernandes and Costa, 2010; Viana et al., 2010). The spatial aggregation and query tools in GIS can be used to evaluate biomass assessment where different layers or themes can be combined and perform analysis between different objects on those layers or within a single layer (Stanbury and Starr, 1999).

The literature survey shows that previous studies on biomass assessment in Nepal have analyzed supply and demand status of fuelwood at the community level without considering all types of biomass sources, mainly fuelwood, crop residues, and animal dung (Schreier et al., 1991; Marzoli and Drigo, 2014). There is a significant lack of literature in geospatial distribution of these biomass fuels. Therefore, this study presents a geospatial mapping model to determine the spatial distribution or supply potential and demands of key biomass sources that are commonly used for household energy use. This is the first study in biomass resource mapping that presents an integrated information on key biomass sources (fuelwood, crop residues and dung). The fuelwood supply potential was evaluated using GIS tool. The crop residues and dung were measured through field surveys and lab experiments respectively, which provide better estimation of biomass sources. The results are useful in prioritizing different energy technologies to achieve clean cooking target of the United Nations. Furthermore, we anticipate that the biomass mapping model is also applicable in the context of other developing countries, where rural communities predominantly rely on biomass for household energy needs, and a complete replacement is not practically feasible in the foreseeable future (UN, 2018). The remainder of the paper is organized as follows. Section 2 describes the materials and methods of the study, mainly the data collection, survey and field experiments and measurements, and sampling methodology used in biomass mapping. Section 3 presents the GIS model for determining the geospatial distribution of forest biomass. Section 4 describes the results and discussion, and finally Section 5 summarizes the main findings of the study.

2. Materials and methods

2.1. Study areas

The study was designed considering three topographically different districts, which are characterized by different types of biomass sources and variations in spatial distribution, agricultural production, and livestock management. To represent these variations, Bajhang, Lamjung, and Morang were selected, which represent mountains, hills, and lowlands respectively as shown in Fig. 1. For convenience, the names of districts are replaced by the corresponding region, i.e. mountains, hills and lowlands throughout the paper.

Covering the area of 3,422 km² and the altitude variation from 900 to 7,077 m AMSL, Bajhang holds forest and arable lands of 43.7% and 7.9% respectively. Lamjung is a hilly district with altitude variation from 385 to 8,162 m AMSL and covering an area of 1,691 km². The forest and arable lands are 55.2% and 36.8% respectively. Similarly, Morang covers an area of 1,855 km², which is categorized as a lowland district with an altitude variation from 60 to 2,410 m AMSL. As compared to other two districts, Morang has relatively higher share of arable land (56.7%) but lower share of forest land (24.3%) (CBS, 2014; DFRS, 2018).

Fuelwood is the main energy source for almost all households in the

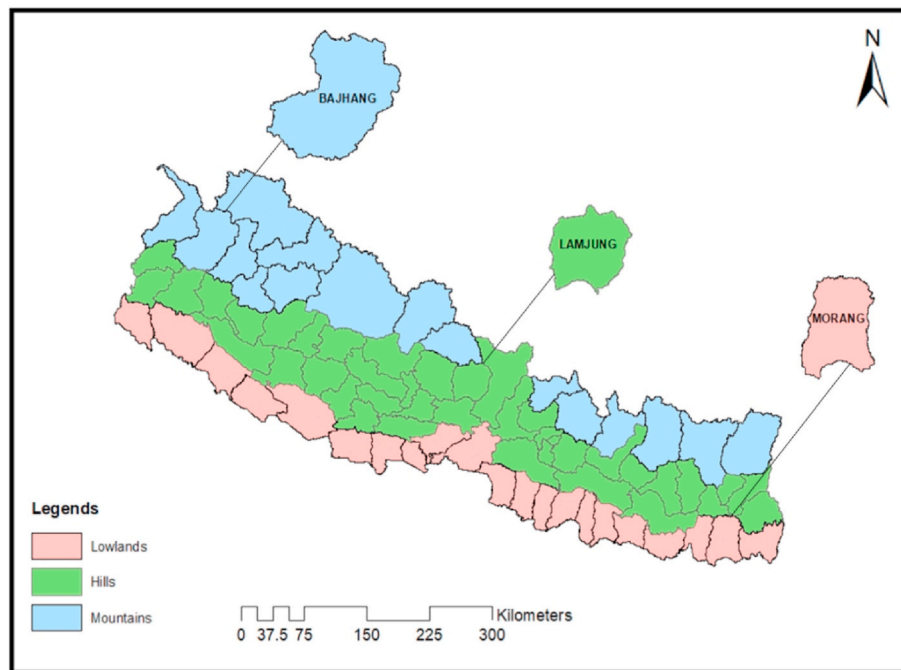


Fig. 1. Research areas for biomass spatial mapping.

mountains, whereas this share is about 70% in hills and 45% in lowlands where the households use other fuel types such as dung cake, LPG, kerosene and biogas. About 25% of these households burn dung cake in lowlands whereas no such households exist in hills and mountains (CBS, 2011). The seasonal variations of temperature and weather are summarized in Table 1, which shows significant differences in climate in three regions. The mountains are characterized by high elevation and cold climate, where the temperature is usually below 10 °C. The hills are characterized by mid elevation and mild climate, and the lowlands are characterized by the lowest elevation with high temperature and humid climate. The temperature ranges in the lowlands are 25–40 °C.

2.2. Data collection and methodology

The data used in the study were collected from household surveys conducted in each geographical region and complemented by GIS tool and secondary data from the literature. The methodology adopted for biomass resource assessment is shown in Fig. 2. The fuelwood supply potential was assessed using spatial GIS techniques. We used Woodfuel Integrated Supply-Demand Overview Mapping (WISDOM) method to assess the supply potential of fuelwood where accessibility was determined based on cost-distance algorithm (Masera et al., 2006). The WISDOM model uses geo-referenced socio-demographic and natural resource data, which integrates relevance data of fuelwood from multiple sources (Masera et al., 2006).

In case of crop residues and dung, the supply potential was assessed

through household surveys and field experiments. The field experiments were conducted to measure dung, crop residues and biomass utilization for household energy uses. Similarly, the biomass demand was determined by assessing the prevailing energy use patterns of households. All findings were synthesized in terms of annual per capita and mapped at the lowest administrative unit of the district, defined as a community unit (CU) in this study. The CUs manage community forests in most cases by introducing local forest regulations, and in some cases, provide technical assistance to community groups for forest management. Hence, biomass information is crucial to formulate regulations on fuelwood usage and thus contributes toward secure supply and distribution of fuelwood in the communities.

2.2.1. Sample households and survey

The probability proportional to size (PPS) sampling method was used to select sample households in different CUs in each district. The households using at least one type of biomass for cooking and space heating were selected. For the sample size of households in each district, we followed a rule of thumb of 10–15 observations as per the United Nations’ recommendation for household surveys (Babyak, 2004). As there are five combinations of fuel usage (fuelwood only, fuelwood and biogas, fuelwood and LPG, fuelwood and dung cake, and fuelwood, dung cake and crop residues), we assumed that a sample size of 80 households is adequate to characterize the variations of households’ energy use in each CU.

Household surveys were conducted using general and closed modes.

Table 1 Average temperature and precipitation in different research areas (Adhikari and Adhikari, 2021).

Season	Parameter	Mountains	Hills	Lowlands
Pre-monsoon (April–May)	Maximum temperature (°C)	10–15	15–20	30–35
	Minimum temperature (°C)	0–5	5–10	15–20
	Precipitation (mm)	100–200	200–400	200–400
Monsoon (August–September)	Maximum temperature (°C)	15–20	20–25	30–35
	Minimum temperature (°C)	5–10	10–15	20–25
	Precipitation (mm)	1,000–1,500	1,500–2,000	1,000–1,500
Winter (December–January)	Maximum temperature (°C)	5–10	10.1–15	20–25
	Minimum temperature (°C)	–5 to 0	0–5	10–15
	Precipitation (mm)	100–200	50–100	30–50

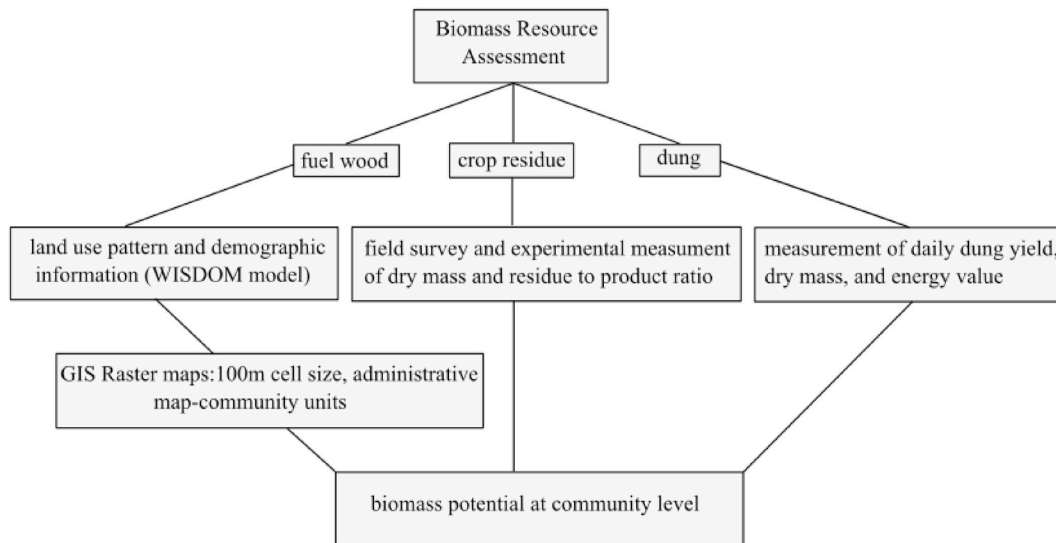


Fig. 2. Methodology for biomass resource assessment.

The purpose of the two modes is to acquire information both on current biomass utilization status as well as measure biomass supply potential for different seasons through field experiments. The questionnaire for general survey was structured to collect information about household demographics, cooking and space heating energy uses, fuelwood collection, crop harvesting methods and livestock management. Similarly, the closed survey was conducted to measure the consumption of fuel and to evaluate the supply potential of crop residues and livestock dung for energy uses. Further details of the methods are discussed in the next section.

2.2.2. Lab experiment for moisture content and dry mass

An important part of this study was the experimental measurement of moisture content of biomass fuels (fuelwood, crop residues, and dung) and oven-dried (OD) weight or dry mass. The experimental method adopted to determine dry mass is shown in Fig. 3. The moisture content was measured in two stages, one with reference to sun-dried mass and other oven-dried in a temperature-controlled muffle furnace. We measured moisture content and oven-dried weight of selected fuelwood, crop residues and dung. First the samples of biomass were collected at field and brought into lab by placing them in tightly packed plastic bags. After a few days, the samples were sun-dried for 40–45 days. Then the samples were heated in the muffle furnace at a uniform temperature of 103 °C ±5 °C up to 14 h until dry mass was achieved. The weights of

samples were measured every 4 h, and the oven –dried weights of sample and the moisture content were determined. The moisture contents of fuelwood and dung were determined from the average of three samples. Three samples were taken for each type of crop residues. The uncertainty in the measurements of dry weight and moisture content is ±0.1%.

3. Description of the GIS model

The GIS sheets with different layers of topography, administrative boundary, population settlements and road networks were collected from the Department of Survey, Government of Nepal (DoS, 2017) as inputs in the geospatial model. Similarly, the land cover raster maps of the districts were obtained from the work of (Uddin et al., 2015), which were prepared from 30 m Landsat TM data for the year 2010. These maps have classified land into twelve different uses and cover four types of forests (needle leaved open, needle leave closed, broadleaved open and broadleaved closed), shrub-land, agricultural land, bare area, built-up area, river, lake and snow/glacier as shown in Table 2. Likewise, the Digital Elevation Map (DEM) of 30 m spatial resolution was obtained from ASTER Global DEM data, which is a joint product of the Ministry of Economy, Trade, and Industry of Japan, and the US National Aeronautics and Space Administration (NASA). Arc GIS 10.1 was used to model the biomass spatial distribution or the supply potential of each

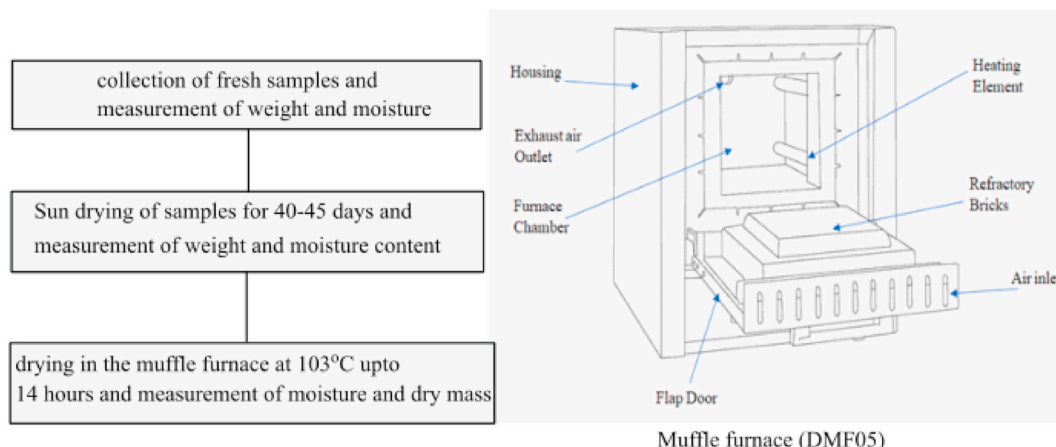


Fig. 3. Schematic of the experimental measurement procedure for moisture content and dry mass of biomass fuels.

Table 2

Annual fuelwood increment (kg dry mass/ha) for different land covers at various altitudes (Marzoli and Drigo, 2014; Baral et al., 2009; FAO, 1999; DFRS, 1999; DFRS, 1999; FAO, 1999; DFRS, 2014a; Amatya and Shrestha, 2010).

Land classification	upto 500 m	500–1,200 m	1,200–2,200 m	2,200–3,500 m	>3,500 m
Needle leaved open forest	1,429	1,429	1,753	2,457	2,509
Needle leaved closed forest	3,039	2,541	2,612	3,889	3,889
Broadleaved open forest	2,535	2,535	2,191	3,451	2,502
Broadleaved closed forest	3,242	3,242	3,089	2,883	2,783
Grassland	549	549	549	549	549
Agriculture	612	612	612	612	–
Built up area	550	550	550	–	–

region (ESRI, 2015). The model was developed with the following procedures and assumptions.

3.1. Modeling of biomass supply potential

3.1.1. Fuelwood

The major sources for fuelwood collection in Nepal are national or community forests, private forests, and homestead surroundings and terraced agricultural lands (Mahat, 1987). The distributions of private and homestead surroundings and terraced agricultural lands are uneven for different households and in some cases, the households have no private land to get fuelwood. In many cases, there are specific rules developed by the local community. This study did not consider such limitations of accessibility that preclude households to collect fuelwood while assessing potential. Therefore, the data reported in this study should be used by considering specific accessibility issues in local areas.

The methods to estimate fuelwood supply were based on the work of (Marzoli and Drigo, 2014) in which three key distinct modules for demand, supply and integration were developed for defined minimum spatial boundary. The data from previous studies (Marzoli and Drigo, 2014; Baral et al., 2009; FAO, 1999; DFRS, 2014b; DFRS, 1999; FAO, 1999; DFRS, 2014a) were used to determine mean annual fuelwood increment in terms of dry mass (DM) from different land covers as no single systematic study was available with such information. Mean annual increment is the total biomass produced in a particular area divided by the number of years required to produce it (Amatya and Shrestha, 2010). The results of mean annual increment of biomass are presented in Table 2.

3.1.2. Assessment of crop residues

As the crop residues share a significant portion of household energy use, five major cereal crops: paddy, wheat, maize, millet and barley were evaluated to assess the contribution of crop residues in household energy use. The share of these cereal crops is more than 90% of total agricultural production in mountains, hills, and lowlands (CBS, 2014).

Closed mode survey was carried out in the sample households for three different seasons (post-monsoon, pre-monsoon and monsoon) to determine residue-to-product ratio (RPR) for each crop residue. RPR refers to the ratio of weight of crop residues in air dried form that is available after processing certain amount of harvested crops to the weight of main crop obtained from the same process (Ayamga et al., 2015). The surveys were conducted in these seasons considering crop harvesting times to determine RPR. Nine households in each district were requested to separate all crop residues collected from a predefined land area and process them as usual. The land area was different in each household and varied from 50 to 100 m². The grains and residues were weighed on air-dry basis from 25 to 30 days of crop harvesting, based on which corresponding RPR values were calculated. The crop residues remaining in the field were not considered because of their essential role in maintaining soil nutrients.

The RPR values thus obtained were used to quantify crop residues used for household's energy use. The estimation of crop residues for energy uses were based on following assumptions:

- The cultivated lands were classified into four broad ranges based on the sea-level altitude, which are low (up to 500 m), Moderate (500–1,200 m), High (1,200–1,800 m) and very high (above 1,800 m). Based on this, cropping patterns were labeled according to the information synthesized from survey.
- The RPR values for respective crop residues as obtained from field experiment are presented in Table 3.
- The crop productivity in each CU was derived by averaging yearly productivity of ten year data (2004–2014) which was obtained from the Ministry of Agriculture and Livestock Development, Nepal (MoALD, 2019).
- The potential crop residues for energy uses was evaluated by analyzing four major uses of crop residues, such as building material, mulching/burning, selling and livestock fodder.
- The weight of net crop residues was converted from air-dried to oven-dried form on the basis of corresponding moisture contents.

3.1.3. Experimental measurement of dung supply

By considering availability of crop residues for livestock fodder, the amount of dung supply was quantified by measuring daily dung yield for three different seasons under the following conditions:

- Fresh dung yield of livestock for 24 h and flow analysis of dung from stall to end use were measured for 70 livestock (cattle and buffalo) in each district from the sample households. In order to cope with district sample statistics, the livestock samples were proportionally divided into four categories: mature cattle (>3 yr), young cattle (≤3 yr), mature buffalo (>3 yr), and young buffalo (≤3 yr).
- The dung yield was measured for three different time periods of a year, in which fodder availability was different. Fodder availability was the highest in monsoon: June–September, and the lowest in winter: December–February. Likewise, fodder availability was moderate in pre-monsoon: March–May. The average dung yields in three different seasons are presented in Table 4, which were used to determine the potential energy use.
- To determine the energy potential of dung, household's livestock management practice, dung collection method, and alternative uses of dung were systematically assessed in the survey.

Table 3

Residue to product ratio (RPR) values of crop residues.

Crop residues	No of samples	RPR
Paddy husk	18	0.363 ± 0.14
Paddy straw	18	1.97 ± 0.57
Wheat husk	11	0.82 ± 0.17
Wheat straw	11	1.46 ± 0.39
Maize stalk	11	2.12 ± 0.45
Corn cob	11	0.28 ± 0.05
Corn ear	11	0.29 ± 0.06
Millet husk	11	0.14 ± 0.04
Millet straw	11	1.89 ± 0.53
Barley straw	9	1.52 ± 0.43

3.2. Modeling of household energy demand

The household surveys showed that all the sample households in the mountains exclusively used fuelwood, whereas multiple energy fuel sources were used in hills and lowlands. These sources were fuelwood, biogas, LPG, crop residues, dung cake, kerosene and electricity. There were eight such different combinations of fuel sources to households in hills, whereas there were fifteen in the lowlands. In order to align with the existing national energy statistics of CUs (CBS, 2011), fuel use was categorized into five types: fuelwood only, fuelwood and biogas, fuelwood and LPG, fuelwood and dung cake, and fuelwood, dung cake and crop residues. By determining the "fuelwood equivalent" of crop residues, dung and biogas (Adhikari, 2017), the annual biomass energy use in household was calculated on per capita basis, Table 5. The "fuelwood equivalent" refers to the conversion of other energy sources into equivalent weight of the fuelwood to meet household energy needs (Adhikari, 2017). The values for "fuelwood equivalent" of biogas, crop residues, LPG and dung were taken from (Adhikari, 2017). By utilizing the measured data of moisture contents from the experiment conducted in this study, the weight of biomass was converted into oven-dried form. The annual energy usage per capita was determined through experiments to cook a standard meal in each household considering different fuels (fuelwood, dung, biogas, crop residues and LPG). Since the cooking experiments were carried out in the community households, the moisture contents of fuelwood, crop residues and dung were assumed negligible when estimating the "fuelwood equivalent". Then the annual biomass energy use per capita in each household was determined, Table 5. However, no detailed uncertainty analysis was conducted to determine whether 80 observations are sufficient to capture the degree of variations of biomass usage in various CUs. As energy usage per capita for cooking a standard meal is similar in different areas, we anticipate that the variation in distribution of biomass usage within a CU is small.

4. Results and discussion

The contour maps of annual accessible supply of fuelwood in three different regions are plotted in Fig. 4. It was found that the net annual supplies of accessible fuelwood in lowland, hill, and mountain districts were estimated as 232,950, 43,025, and 44,534 metric tons respectively. On per capita basis, the hill district has the highest fuelwood supply with 257 kg/yr, and the lowland and the mountain districts have 240 kg/yr and 228 kg/yr respectively. The CUs with annual per capita fuelwood supply more than 800 kg/ha lie on the northern part of lowland, where only 5% of the district's population lives. As compared to hill and mountain districts, the distribution of forest and human settlement is highly disproportionate in the lowland district.

The weights of annual supply potential and demand of three types of biomass are summed in terms of fuelwood equivalent to obtain a single value for annual per capita supply and demand of biomass for each CU. Biomass energy of a particular CU was calculated based on the corresponding values presented in Table 5. The annual per capita demand of a

Table 4
Weight of daily fresh dung yield per livestock (kg).

Categories	Location	No of samples	Winter
Young cattle	Lowlands	20	9.5 ± 4.6
	Hills	11	5.5 ± 3.0
	Mountains	21	2.2 ± 1.5
Mature cattle	Lowlands	31	15.8 ± 7.1
	Hills	20	10.2 ± 2.3
	Mountains	32	4.3 ± 1.9
Young buffalo	Lowlands	7	11.3 ± 4.5
	Hills	14	10.3 ± 4.9
	Mountains	8	6.3 ± 2.9
Mature buffalo	Lowlands	12	22.5 ± 6.7
	Hills	25	24.3 ± 6.3
	Mountains	9	16.9 ± 4.3

Table 5
Biomass energy use (oven-dry mass).

Household energy mix	Energy source	Fuelwood equivalent (kg/yr per capita)		
		Lowland district	Hill district	Mountain district
Fuelwood only	Fuelwood	467 ± 183	779 ± 295	713 ± 367
Fuelwood & biogas	Fuelwood	314 ± 195	430 ± 235	-
	Biogas	130 ± 53	216 ± 78	-
Fuelwood & LPG	Fuelwood	405 ± 155	533 ± 249	-
	LPG	70	38	-
Fuelwood & dung cake	Fuelwood	331 ± 172	-	-
	Dung cake	145 ± 116	-	-
Fuelwood, dung cake & crop residues	Fuelwood	235 ± 128	-	-
	Dung cake	161 ± 91	-	-
	Crop residues	61	-	-

particular CU was deducted by the corresponding biomass supply to establish the relationship between biomass supply and demand. By deducting annual biomass demand from the corresponding biomass supply, the net availability of biomass in terms of either surplus or deficit was determined for each CU. It is noted that the positive values indicate biomass surplus, whereas the negative values indicate biomass deficit. The information of each type of biomass on each CU is useful to quantify the amount of particular biomass used. For example, one of the CUs in the lowland (Table 6, Code no. 10) has surplus annual biomass per capita as 92 kg. This shows that there is a potential for reducing fuelwood by 83 kg by utilizing all dung available for biogas production. Similarly, spatial information helps to evaluate the possibility for transporting biomass from abundant CUs to other CUs with biomass deficit. The GIS method is valuable in assessing fuelwood potential to those areas of mountains and hills with complex terrain where alternative methods of assessment require significant cost.

From Table 6, more than 80% CUs have surplus biomass (54 CUs out of 66) in lowlands, where fuelwood can only provide surplus biomass to only 13% CUs (9 CUs). Those CUs with fuelwood surplus lie in northern part of the district and hold typical characteristics of hills with a population share of less than 5% of the district population. Therefore, in lowlands, the higher production of crop residues and dung contributes to reliable supply of biomass for household energy (45 CUs: 70% of CUs). It is worth mentioning that these crop residues and dung as well as fuelwood are directly burned for household energy use, such as cooking and space heating. These results reveal that the currently used crop residues and dung for household energy need to be converted to cleaner biomass fuels, and cleaner cooking technologies should be developed.

Similarly, the fuelwood supply and demand presented in Table 7 for hills show that only three CUs out of 64 have reliable supply of fuelwood. Because of easy availability of fuelwood, no crop residues were used for energy generation whereas the use of dung was limited in the form of biogas. Unlike in lowlands, dung was not burned directly for energy generation. We note that although there was reliable supply of crop residues and dung for about nearly half of total CUs, the fuelwood was over exploited. Despite significant increment in total forest areas in hills, the forest areas have been declining significantly on densely populated areas due to expansion of agricultural areas, settlements and infrastructure development. Hence, there have been uneven spatial distribution of forest areas for which the spatial analysis is crucial to take suitable policy measures and protect forest areas.

Similarly, the results presented in Table 8 for mountains show that only 5 CUs (about 10% of total CUs) had potential to maintain reliable biomass supply and demand. The addition of crop residues and dung was not sufficient to maintain adequate supply in none of the CUs due to relatively lower production of crop residues and dung. The higher

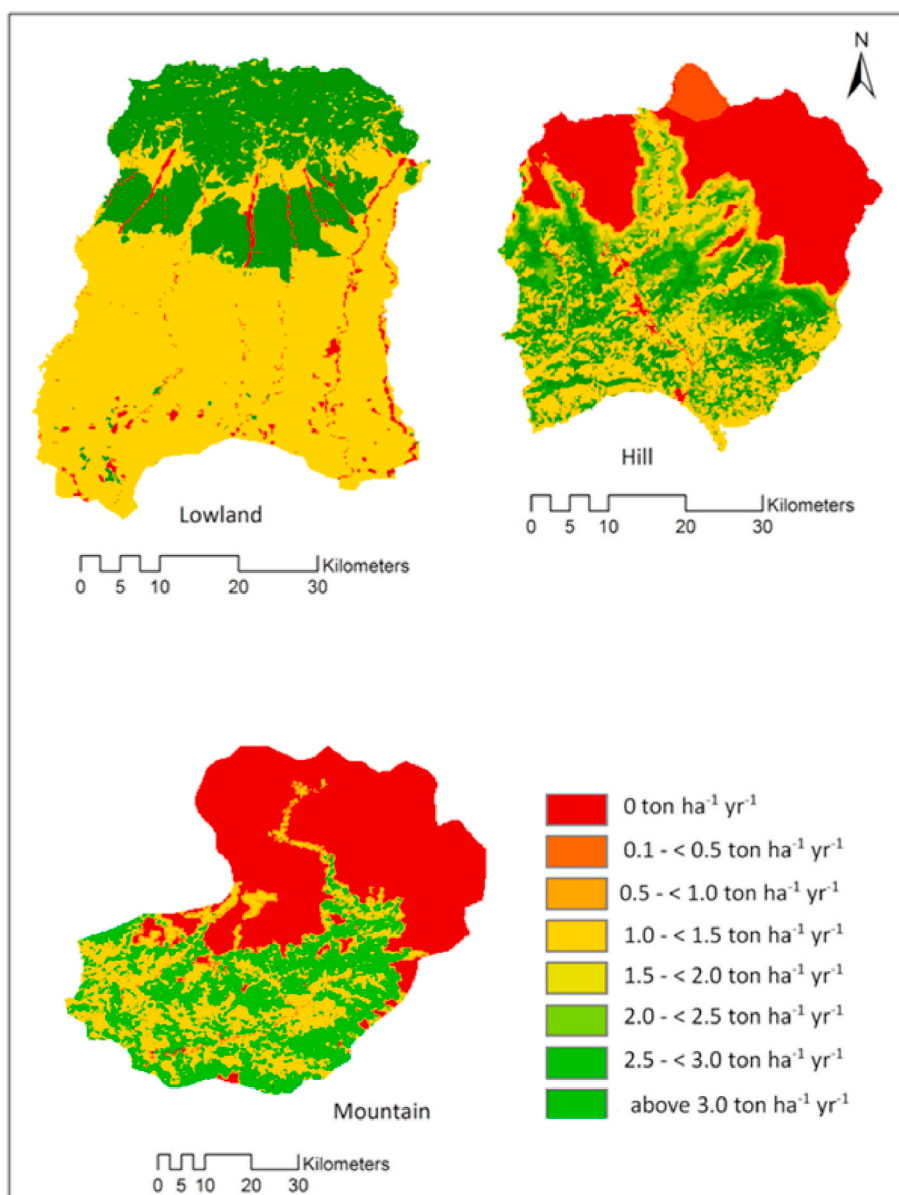


Fig. 4. Contour maps of annual accessible supply of fuelwood in mountain, hill, and lowland districts.

fodder deficiency and less cultivated lands with poor agricultural facilities were found to be the major causes of lower production of dung and crop residues respectively. Therefore, the use of crop residues and dung was quite negligible in mountains, and fuelwood was predominantly used by almost all households.

From the results presented in Tables 6–8, we classified the supply potential of fuelwood, crop residues, and dung into six types with respect to the demand of household energy. The number of households at each CU was taken from national statistics (CBS, 2011). The results are summarized in Table 9.

From Table 9, it is observed that only about 3% biomass adopting households have adequate supply of biomass energy in mountains for which fuelwood has the biggest role. The households with adequate biomass supply in hills and lowlands are 50% and 57% respectively. The forest resources in hills and mountains for most households were relatively greater than that of lowlands. Therefore, consideration of mean annual increment of fuelwood in view of fuelwood harvesting is not worthy from the perspectives of fuelwood users. As such, the households are able to collect fuelwood as per their demand. However, in view of annual supply potential presented in Table 9, the prevailing fuelwood

consumption is inadequate in terms of reliable supply. Further, it is evident that despite higher fuelwood deficits in lowlands compared to hills and mountains, the relatively better production of crop residues and dung was the main reason for sufficient supply of biomass to more than half of biomass adopting households. The results revealed that the available but unutilized crop residues and dung could not play significant roles to meet biomass demand in mountains, whereas the same played a significant role in hills and lowlands. Therefore, despite having sufficient crop residues and dung for household energy use in hills, those were not utilized, resulting in overexploitation of fuelwood. The potential application of dung and crop residues is discussed in terms of resource availability for direct burning. However, these biomass fuels should be converted into cleaner form by intervention of technologies such as biogas and briquette.

The results of present study for annual biomass consumption per capita are compared with the previous studies in Table 10. The data for different biomass fuel supply are the corresponding average of data presented in Tables 7–9. The results for dung and crop residues at CU level are presented in terms of fuelwood equivalent by their respective equivalent coefficient (Adhikari, 2017). Except fuelwood consumption,

Table 6
Biomass supply and demand in CUs of Lowlands in oven-dried form (kg/yr per capita).

Code no.	CU	Supply				Demand	Surplus/Deficit
		Fuelwood	Crop res.	Dung	Total		
1	Amahibariyati	188	83	221	492	370	122
2	Amardaha	220	97	194	511	404	107
3	Amgachhi	188	83	327	598	328	270
4	Babiyabirta	260	113	119	492	384	108
5	Bahuni	404	100	126	630	472	158
6	Banigama	217	112	169	498	430	68
7	Baradanga	281	80	96	457	352	105
8	Bayarban	359	59	178	596	479	117
9	Belbari	452	78	95	625	482	143
10	Bhathigachh	175	56	236	467	375	92
11	Bhaudaha	169	74	192	435	342	93
12	Bhogateni	3,981	54	133	4,168	500	3,668
13	Biratnagar	24	7	41	72	148	-76
14	Buddha Nagar	226	55	97	378	340	38
15	Dadarbairiya	261	75	93	429	341	88
16	Dainiya	168	74	243	485	371	114
17	Dangihat	151	30	43	224	487	-263
18	Dangraha	198	81	234	513	406	107
19	Darbeshha	251	109	155	515	402	113
20	Dulari	97	71	187	355	415	-60
21	Gobindapur	238	105	155	498	384	114
22	Haraicha	215	85	279	579	463	116
23	Hasandaha	227	94	247	568	448	120
24	Hattimudha	207	77	221	505	392	113
25	Hoklabari	224	99	242	565	428	137
26	Indrapur	162	18	63	243	474	-231
27	Itahara	354	94	139	587	465	122
28	Jante	2,481	93	56	2,630	498	2132
29	Baijanathpur	142	83	397	622	392	230
30	Jhorahat	157	69	581	807	389	418
31	Jhurkiya	243	132	85	460	367	93
32	Kadamaha	183	97	184	464	367	97
33	Kaseni	352	111	119	582	446	136
34	Katahari	138	75	179	392	426	-34
35	Kerabari	1,133	62	39	1,234	494	740
36	Keraun	255	93	184	532	464	68
37	Lakhantari	228	101	140	469	350	119
38	Letang	699	47	41	787	489	298
39	Madhumalla	442	89	91	622	491	131
40	Mahadewa	206	85	165	456	352	104
41	Majhare	176	58	212	446	340	106
42	Motipur	328	144	99	571	438	133
43	Mrigauliya	396	55	141	592	468	124
44	Nocha	183	126	129	438	344	94
45	Pathari	126	32	59	217	486	-269
46	Patigaun	3,392	64	151	3,607	578	3,029
47	Pokhariya	197	56	195	448	345	103
48	Rajghat	234	103	252	589	470	119
49	Ramitekhola	3,788	45	321	4,154	583	3571
50	Rangeli	154	54	165	373	400	-27
51	Sanischare	127	41	70	238	485	-247
52	Sidraha	293	85	193	571	426	145
53	Sijuwa	2,46	158	175	579	453	126
54	Simhadevi	3,601	66	155	3,822	557	3,265
55	Sisabanijahada	217	52	86	355	385	-30
56	SisbaniBadahara	197	115	186	498	391	107
57	Sorabhag	251	89	146	486	377	109
58	Sundarpur	286	56	106	448	479	-31
59	Takuwa	214	89	142	445	358	87
60	Tandi	1,287	69	117	1,473	586	887
61	TankiSinuwari	83	36	56	175	425	-250
62	Tetariya	223	98	236	557	398	159
63	Thalaha	217	87	142	446	354	92
64	Urlabari	89	25	52	166	483	-317
65	Warangi	4,080	32	135	4,247	594	3,653
66	Yangshila	2,184	47	63	2,294	586	1,708

there are only a few limited studies to compare the results of present study. The results are compared with respective to geographical regions. The average fuelwood consumption data was obtained from Table 5. The average fuelwood consumption was found within the range of data reported by previous studies in all topographic regions. Similarly, we

found that dung consumption in lowlands is significantly lower than that reported in reference (Behera et al., 2015). This difference could be due to variations in livestock per holding and fodder availability. The annual per capita supply potential of crop residues in hills from previous study (80 kg) is significantly lower than the present study (207 kg), which

Table 7
Biomass supply and demand in CUs of Hills in oven-dried form (kg/yr per capita).

Code no.	CU	Supply				Demand	Surplus/Deficit
		Fuelwood	Crop res.	Dung	Total		
1	Archalbot	161	59	358	578	747	-169
2	Baglungpani	289	112	310	711	688	23
3	Bahundanda	291	84	235	610	717	-107
4	Bajhakhet	420	55	254	729	628	101
5	Bangre	332	89	294	715	684	31
6	Bansar	509	58	285	852	761	91
7	Besishahar	9	7	37	53	120	-67
8	Bhalayakharka	256	76	318	650	641	9
9	Bharte	243	55	314	612	713	-101
10	Bhoje	675	79	217	971	763	208
11	Bhorletar	108	42	159	309	618	-309
12	Bhoteodar	34	19	98	151	460	-309
13	Bhujung	1,174	66	271	1,511	792	719
14	Bhulbhule	840	88	246	1,174	761	413
15	Bichaur	350	79	259	688	657	31
16	Chakratirtha	86	55	199	340	593	-253
17	Chandisthan	60	34	304	398	677	-279
18	Chandreshwar	212	98	298	608	598	10
19	Chiti	87	66	193	346	666	-320
20	Dhamilikuwa	101	52	194	337	583	-246
21	Dhodeni	693	55	237	985	775	210
22	Dhuseni	263	85	357	705	586	119
23	Dudhpokhari	474	84	250	808	721	87
24	Duradanda	243	49	296	588	661	-73
25	Gauda	514	129	251	894	707	187
26	Gaunshahar	102	63	160	319	651	-332
27	Uttarkanya	566	67	348	981	775	206
28	Ghanpokhara	547	59	205	811	728	83
29	Ghermu	423	43	255	721	717	4
30	Gilung	487	118	297	902	721	181
31	Hiletaksar	344	94	404	842	757	85
32	Ilampokhari	532	147	263	942	749	193
33	Isaneshwar	137	30	253	420	789	-369
34	Jita	305	105	292	702	575	127
35	Karapu	513	101	260	874	699	175
36	Khudi	267	75	229	571	688	-117
37	Kolki	376	126	249	751	725	26
38	Kunchha	237	56	332	625	494	131
39	Maling	543	107	400	1,050	783	267
40	Mohariyakot	345	93	213	651	769	-118
41	Nalma	454	76	354	884	788	96
42	Nauthar	221	53	334	608	729	-121
43	Neta	232	65	342	639	765	-126
44	Pachok	512	61	282	855	769	86
45	Parewadanda	110	68	268	446	741	-295
46	Pasgaun	575	54	295	924	793	131
47	Phaleni	800	33	335	1,168	790	378
48	Purankot	480	96	365	941	744	197
49	Pyarjung	450	155	335	940	723	217
50	Ramgha	121	36	196	353	772	-419
51	Samibhanjyang	197	29	258	484	576	-92
52	Shribanjyang	134	65	341	540	642	-102
53	Simpani	116	39	208	363	734	-371
54	Sindure	348	114	242	704	698	6
55	Sundarbazar	35	8	122	165	760	-595
56	Suryapal	239	55	337	631	744	-113
57	Tadhring	487	132	334	953	738	215
58	Taksar	106	55	234	395	663	-268
59	Tarku	314	50	415	779	768	11
60	Tarkughat	108	40	238	386	782	-396
61	Udipur	143	62	235	440	784	-344

could be due to lower availability of cultivated land (0.15 ha/capita) than that of the hills in this study (0.37 ha/capita) (CBS, 2011). The supply of annual crop residues of lowlands (395 kg/capita), which is similar to the topographic region of India, was found significantly lower than that of India (602 kg/capita). In lowlands, the maximum annual crop residues supply was 395 kg/capita (Table 6). The main reason for this significant difference is the variation in yield (kg/ha) of cereal crops as the production of main crops has positive correlation with the crop residues (Ayamga et al., 2015). The yield of wheat in Punjab, India is 4,

693 kg/ha (Singh, 2015), whereas it is only 2,396 kg/ha in lowlands of Nepal (CBS, 2014). Except geographical and socio-economic variations, it is not clear whether the biomass reported in other studies were oven-dried dry mass or not.

The above results provide important data for designing energy programs for CUs, such as in prioritizing their energy needs and supply potential of different biomass sources. For example, CUs with surplus biomass can utilize mix of three biomass sources and manage efficiently their supply and demand. Similarly, CUs with biomass deficit can focus

Table 8
Biomass supply and demand in CUs of mountains in oven-dried form (kg/yr per capita).

Code no.	CU	Supply				Demand	Surplus/Deficit
		Fuelwood	Crop res.	Dung	Total		
1	Banjh	87	19	105	211	516	-305
2	Bhairavnath	93	6	107	206	516	-310
3	Bhamchaur	133	6	106	245	645	-400
4	Bhatekhola	90	5	123	218	551	-333
5	Byasi	204	6	119	329	551	-222
6	Chainpur	178	4	71	253	516	-263
7	Chaudhari	78	7	167	252	516	-264
8	Dahabagar	481	11	95	587	645	-58
9	Dangaji	162	15	129	306	551	-245
10	Datola	560	7	154	721	645	76
11	Daulichaur	392	7	62	461	645	-184
12	Deulek	56	3	110	169	551	-382
13	Deulikot	95	7	64	166	551	-385
14	Dhamena	910	12	161	1,083	551	532
15	Gadaraya	403	6	155	564	645	-81
16	Hemantawada	41	7	130	178	516	-338
17	Kadel	147	4	90	241	551	-310
18	Kailash	535	13	667	1,215	551	664
19	Kalukheti	84	8	174	266	551	-285
20	Kanda	1143	26	429	1,598	645	953
21	Kaphalseri	162	6	73	241	551	-310
22	Khiratadi	118	10	70	198	516	-318
23	Koiralakot	105	6	139	250	551	-301
24	Kotbhairab	63	7	140	210	516	-306
25	Kotdewal	127	6	125	258	551	-293
26	Lamatola	206	9	267	482	516	-34
27	Lekgaun	201	3	97	301	645	-344
28	Luyata	221	17	141	379	516	-137
29	Majhigaun	108	4	121	233	551	-318
30	Malumela	109	20	203	332	516	-184
31	Mastadev	338	6	464	808	645	163
32	Matela	123	11	145	279	516	-237
33	Maulali	70	6	155	231	551	-320
34	Melbisauni	444	6	131	581	645	-64
35	Parakatne	161	14	128	303	551	-248
36	Patadebal	140	4	190	334	551	-217
37	Pauwagadhi	118	5	245	368	551	-183
38	Pipalkot	164	8	110	282	551	-269
39	Royal	107	12	82	201	516	-315
40	Rilu	170	3	81	254	645	-391
41	Rithapata	226	7	147	380	516	-136
42	Senpasela	141	4	80	225	645	-420
43	Subeda	137	5	91	233	516	-283
44	Sunikot	258	4	216	478	551	-73
45	Sunkuda	142	12	74	228	551	-323
46	Surma	267	4	91	362	645	-283
47	Syadi	100	6	85	191	645	-454

Table 9
Share of households with biomass surplus/deficit as a percent of biomass supply.

Biomass surplus/deficit (% of biomass supply)	Lowlands (% of households)	Hills (% of households)	Mountains (% of households)
< - 20% (Highly unreliable)	30	9	95
-10 > -20% (Unreliable)	11	38	1
-10 < 0% (Moderate)	4	3	1
0 < 10% (Adequate)	3	11	1
10 < 20% (Reliable)	16	22	1
>20% (Highly reliable)	38	17	1

to utilize other energy technologies to reduce biomass use. It is worth mentioning that special attention should be given to those CUs in lowlands, where crop residues and dung are extensively used for cooking and space heating, to prevent indoor air pollution as well as detrimental effects on soil fertility. This is because burning of crop residues produce more indoor pollution than fuelwood. Therefore, biogas technology can

be promoted to minimize burning of dung and use of crop residues for household energy use. Furthermore, indoor and outdoor air pollution due to direct burning of biomass in traditional stoves must be reduced through multi-tier framework for cooking and use of novel technologies in biomass fuel conversion and cooking stoves with higher combustion efficiency. These results clearly indicate that the current use of ICS and promotion policies are not adequate to meet the clean cooking target of sustainable development goal (SDG: 7) of the United Nations.

5. Conclusions

This paper presents a geospatial mapping model for estimating biomass energy sources considering the case of Nepal. Three types of biomass fuels: fuelwood, crop residues, and animal dung were considered, which are commonly used for household energy use. For this, three geospatially different regions of Nepal, categorized as lowlands, hills, and mountains, were investigated. These regions are characterized by significant spatial variations in biomass distribution and supply potential. In this model, the supply potential of fuelwood was assessed using Geographical Information System (GIS) tool, and the potential of crop residues and dung was determined by conducting household surveys

Table 10

Comparison of results of annual biomass consumption per capita with previous studies.

Biomass	Location	Source	kg/capita
Fuelwood consumption	Lowland	(Behera et al., 2015)	246
		(Thapa and Chapman, 2010)	482
		(Shrestha, 2007)	382
		(Rijal, 2018)	535
	Hill	Present study	351
		(Webb and Dhakal, 2011)	683
		(Bajracharya, 1983)	940
		(Rijal, 2018)	561
	Mountain	Present study	581
		(Fox, 1984)	570
		(Rijal, 2018)	1,310
		(Christensen et al., 2009)	1,323
Dung consumption	Lowland	Present study	713
		(Behera et al., 2015)	264
Fuelwood supply	Hill	Present study	153
		(Pokharel, 2000)	346
Dung supply	Hill	Present study	333
		(Pokharel, 2000)	309
Crop residues supply	Hill	Present study	270
		(Pokharel, 2000)	80
		Present study	207
	Punjab, India (low land)	(Singh, 2015)	602
		Present study	152

and experimental measurements. As compared to previous studies, we experimentally measured “dry-mass” of dung and crop residues and their supply potential from field surveys and spatial mapping of fuel wood supply. Therefore, these data and information are an important addition to the current literature and are valuable in planning energy programs at CU level. The main findings are summarized as follows.

- crop residues and dung were extensively used in lowlands because of low fuelwood supply, whereas the use of crop residues and dung was negligible in hills and mountains due to relatively easier access to forest biomass
- about 3% households in mountains, 50% households in hills, and 57% households in lowlands have secure access to biomass sources
- despite significant availability of crop residues and dung in hills, they were not utilized for household energy use, which resulted in over-exploitation of fuelwood
- The uneven spatial distribution of biomass in densely populated areas led to overutilization of biomass, whereas underutilization of biomass in less populated areas. Hence, the spatial distribution is crucial in formulating energy policies and programs.

We anticipate that this biomass mapping model is also applicable in the context of other developing countries, where rural communities predominantly rely on biomass for household energy needs, and its complete replacement is not practically feasible in the foreseeable future. Biomass spatial information is crucial in designing new policies and developing new biomass energy technologies to achieve clean cooking energy targets of sustainable development goal (SDG: 7) of the United Nations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.deveng.2021.100070>.

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