Professional Leave Report Cover Sheet

Name: Mohan Dangi

Department: Geography & City & Regional Planning

College: Social Sciences

Leave taken: (●) Sabbatical ( ) Difference in Pay ( ) Professional Leave without Pay

Time Period:
- ( ) Fall
- ( ) Spring
- (●) Academic Year 2022-2023
- ( ) Other

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Sabbatical Leave AY 2022-2023 Report

College of Social Sciences

Submitted to

Dr. Elizabeth Lowham
Dean, College of Social Sciences
California State University (CSU), Fresno

Faculty Member

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Project Summary

Prof. Mohan B. Dangi was granted a sabbatical leave in the academic year (AY) 2022-2023 with the following three objectives:

1.) Design, develop, and teach an urgently needed Introduction to Environmental Engineering course at the Central Department of Environmental Science (CDES), Tribhuvan University (TU), Kirtipur, Nepal to fill curricular gaps and deliver the course online, essential during current pandemic conditions.
2.) Further advance research using life cycle assessment (LCA) for solving problems concerning municipal solid waste (MSW) management in Kathmandu, Nepal.
3.) Publish at least one manuscript covering LCA of MSW or earthquake recovery work covering the 2015 Nepal earthquake that the CSU, Fresno community, partially funded.

Completed Activities

Dr. Dangi spent his sabbatical leave at Tribhuvan University, Nepal as a Fulbright U.S. Scholar, where he designed an Introduction to Environmental Engineering course and submitted it to the TU Subject Committee for approval. The LCA fieldwork was also completed before the end of the Fulbright tenure on March 28, 2023. Manuscripts covering the LCA work, the 2015 Nepal earthquake, post-COVID waste management in developing countries, and others are being submitted to journals for publication. Prof. Dangi together with his research group was able to publish three manuscripts during the sabbatical period. The published manuscripts are listed below and attached in Appendix A.

Dangi, M.B., Malla, O.B., Cohen, R.R.H., Khatiwada, N.R., and Budhathoki, S. 2023. Life cycle assessment of municipal solid waste management in Kathmandu city, Nepal – An impact of an incomplete data set. *Habitat International*, 139, 102895. https://doi.org/10.1016/j.habitatint.2023.102895.

Shrestha, P.P., Ghimire, A., **Dangi, M.B.**, and Urynowicz, M.A. 2023. Development of a municipal solid waste management life cycle assessment tool for Banepa Municipality, Nepal. *Sustainability*, 15(13), 9954. https://doi.org/10.3390/su15139954.

Shrestha, S., Poudyal, K.N., Bhattarai, N., **Dangi, M.B.**, and Boland, J.J. 2022. An Assessment of the impact of land use and land cover change on the degradation of ecosystem service values in Kathmandu valley using remote sensing and GIS. *Sustainability*, 14(23), 15739. DOI: https://doi.org/10.3390/su142315739.

In addition, ten manuscripts are currently being reviewed by various Q1 journals.

Related Achievements

While the sabbatical leave was granted for the AY 2022-2023, the Fulbright fellowship was only awarded for seven months beginning on August 29, 2022, and ending on March 28, 2023. To provide the details of the overlapping awards, Dr. Dangi has included both sabbatical and Fulbright-related tasks with appropriate objectives, activities, progress, and comments in Table 1 below.

Table 1. Overview of Fulbright U.S. Scholar Dr. Dangi's activities during his sabbatical leave in Nepal.

Item #	Objectives	Activities	Progress(es)	Comments
1a	Teaching	Design and delivery of an Introduction to Environmental Engineering course both in-person and online.	The course has been designed and the preparation for the offering is underway.	The course was approved by two outside experts (Cohen, Colorado School of Mines; Paterson, Arizona State University). It will be offered once it is approved by the TU Subject Committee. Prof. Dangi will assist the CDES faculty with the delivery when offered. Instead, Dr. Dangi taught ENV 611: Pollution Control Technology – Solid Waste Engineering to 16 master's students and a seminar course to 22 Ph.D. students at CDES.
1b	Teaching	Bring three guest speakers into the	Completed.	Belbase (United Arab Emirates University, Kanwar (Iowa State University), and Townsend-

		classroom.		Small (University of Cincinnati) gave the guest lectures.
1c	Teaching	Organize biweekly seminars on emerging environmental engineering topics in low-income countries by inviting experts at Tribhuvan University.	Completed.	Twelve biweekly seminars were offered to CDES, TU, Kathmandu University, Nepal Academy of Science and Technology, and the U.S. Embassy. They include Bhanu (University of California, Riverside), S. Giri (Kathmandu Institute of Applied Sciences), Jones (University of Nevada, Reno), Jefferson (Fort Valley State University), Campins (University of Central Florida), Gunasekaran (University of Wisconsin, Madison), Mascal (University of California, Davis). While Jones, Gunasekaran, and Mascal gave two seminars each and Professor Dangi also presented two talks.
2a	Research	LCA of MSW management in Kathmandu	Dr. Dangi and his research team have gathered data, conducted field visits and key informant interviews, and the analysis and writing are nearly done.	A manuscript covering this work is expected to be submitted to the *Waste Management* journal soon.
2b	Research	Study of the efforts of alpine solid waste collection by the International Mountaineering Museum in Pokhara	Prof. Dangi visited the museum in September 2022 and learned about the Japanese experience.	The information was valuable to conduct the fieldwork on Everest.
2c	Research	Study of solid waste management (SWM) in Everest	Realizing the research need of the host institution, this was added. Focus group interviews and a field visit took place in October 2022 and the preliminary results were presented at the South Central	A manuscript covering this task is expected to be ready soon.

			Asia (SCA) Fulbright Conference in Kochi. Also, the abstract has been accepted for an oral presentation at the 2024 Global Waste Management Symposium in California.	
2d	Research	SWM in Ghandruk	To complement the work in Everest and continue with TU's research in the Annapurna region, this activity was added when there were no classes in December 2022.	A manuscript covering this work is being published in the *Habitat International* journal.
2e	Research	MSW Study in Ghorahi Sub-Metropolitan City	As requested by Ghorahi Sub-Metropolitan City, surveying and sampling of waste took place in 100 Ghorahi households for three days in February 2023.	A manuscript involving this work will be prepared by January 2024.
3a	Fulbright Training	Training of Environmental Workforce in Ghorahi Sub-Metropolitan City	Four national and international experts including Dr. Dangi provided a daylong training to 42 attendees about SWM and urban environmental topics.	The Mayor of Ghorahi attended the entire meeting and is very eager to implement the training recommendations.

3b	Fulbright Training	Training of Environmental Workforce in Myanglung Municipality	Three national and international experts including Prof. Dangi provided a daylong training to 35 participants about solid waste and urban environmental management.	While the solid waste problem is still in its early stages, the mayor seems very committed and attended the entire meeting.
3c	Fulbright Training	Fulbright Forum: Global Tools and Techniques to Manage Local Solid Waste Problems	Dr. Dangi delivered this talk at the Innovation Hub of the U.S. Embassy in Kathmandu and the Federation of Nepalese Chambers of Commerce on March 22, 2023, and 40 people attended it.	This was the last Fulbright talk of Prof. Dangi which also served as a presentation for Kathmandu Metropolitan City.
4a	Field Visit	Karaute Danda Landfill	Professor Dangi, three other national and international experts, and the mayor and his staff visited the landfill serving Ghorahi on February 2, 2023.	It was realized that the landfill was full of plastic waste and lacked proper compaction and leachate treatment.
4b	Field Visit	Banchare Danda Landfill	Dr. Dangi and two of his hosts visited the landfill serving Kathmandu Metropolitan City on February 21, 2023.	The visit lasted nearly ten hours and included the observation of old and active landfill sites and a few town hall meetings in which nearly 30 people participated.

4c	Field Visit	Myanglung Dumping Site	Dr. Dangi, two other national and international experts, the mayor, and his staff visited the dumping site on March 11, 2023.	Waste is handled in a rudimentary way in a crevasse, and this could directly impact the Tamor River downstream.
5a	Fulbright SCA Regional Travel Program (RTP) Grant	Indian Institute of Technology (IIT) Delhi	Professor Dangi gave a similar talk to his Fulbright Forum presentation at the Department of Civil Engineering at the Indian Institute of Technology Delhi on February 7, 2023.	Dr. Dangi and an IIT Delhi Ph.D. student visited the Okhla Dumping Site on February 8, and the conversation is underway for a review article and collaboration.
5b	Fulbright SCA RTP Grant	Indian Institute of Technology Jodhpur	Dr. Dangi gave a talk to the Department of Chemical Engineering (February 10), the Faculty Board (February 10), and the University community (February 13).	All three talks were well attended and a partnership for research and curriculum development in solid waste engineering with the Department of Chemical Engineering is underway.
5c	Fulbright SCA RTP Grant	Indian Institute of Technology Bombay	Prof. Dangi gave a similar talk to his Fulbright Forum presentation to the Environmental Engineering and Science Department on February 15, 2023, and the room was	Dr. Dangi and an IIT Bombay master's student visited the Kanjurmarg Dumping Ground on February 16, and the conversation is underway for a review article and collaboration.

			packed with attendees.	
6a	Fulbright SCA Conference	Kochi, Kerala, February 27-March 1, 2023	Dr. Dangi presented a talk, How to Keep Mt. Everest Clean?	It was the first talk of the conference on February 27 and was well attended. The next day, Dr. Dangi met with Kochi solid waste officials to learn about their solid waste management efforts.
6b	Fulbright SCA Conference	Kochi, Kerala, February 27-March 1, 2023	Dr. Dangi took part in the Roundtable for Teaching Scholars: Learning from Each Other on February 28, 2023.	It was very helpful to understand and relate teaching in terms of what has worked and what hasn't among the different scholars in the SCA region.
7a	Lumbini Technological University	Tulsipur, Dang, January 20, 2023	Met with the Vice-Chancellor and Registrar of the University and provided feedback on how to develop a curriculum for their new Institute of Engineering.	There was a follow-up meeting with the registrar in Kathmandu, and Dr. Dangi offered help wherever he could.
7b	Global Conference on Environment & Sustainability	March 26, 2023	The new dates for the postponed conference because of COVID-19 were announced for June 9-11, 2023.	The details of the proposed conference can be found here: https://www.nepallivetoday.com/2023/03/26/nepal-to-host-global-conference-on-environment-and-sustainability/
7c	Policy Recommendations	Various Dates	Met the President of Nepal, Bidya Devi Bhandari, Former Prime Minister, K.P. Sharma Oli, former ministers, members of parliament, Joint Secretary,	In each of the meetings, Dr. Dangi offered policy feedback related to solid waste management, higher education, integrated environmental management, and academic partnerships with U.S. universities. As a result, a new memorandum of understanding was signed between Tribhuvan University and the University of Nevada, Reno on January 2, 2023.

			Ministry of Foreign Affairs, and Vice Chancellor of Tribhuvan University.	

Opportunities and Challenges

As COVID-19 had seriously impacted the teaching and subsequent examination across TU campuses in Nepal, the enrollment of new students was delayed by nearly 15 months. As such teaching and offering a course became challenging at the beginning of the Fulbright (sabbatical) tenure. Based upon the priority of the host department and in consultation with the Fulbright Binational Commission in Kathmandu, Dr. Dangi included a few other research topics as outlined in section 2 above in Table 1. Fortunately, Dr. Dangi could teach a course in Solid Waste Engineering course before his Fulbright tenure ended.

A good part of the Fulbright/sabbatical assignment was student learning from the delivery of seminars by 15 guest lectures and biweekly seminars of which seven were delivered by former Jefferson Science Fellows from the [U.S.] National Academies of Sciences, Engineering, and Medicine.

When the Fulbright fellowship ended on March 28, 2023, Prof. Dangi continued working on his LCA, the 2015 Nepal earthquake, and the ten manuscripts that are presently being reviewed between March 29, 2023, and the beginning of the new AY in 2023-2024.

APPENDIX A

Copies of the three manuscripts published as a result of the sabbatical leave.

sustainability

MDPI

Article

Development of a Municipal Solid Waste Management Life Cycle Assessment Tool for Banepa Municipality, Nepal

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Abstract: In this study, the life cycle assessment (LCA) method has been used to evaluate the environmental impacts of various municipal solid waste (MSW) management system scenarios in Banepa municipality, Nepal, in terms of global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), abiotic depletion potential (ADP), and photochemical ozone creation potential (POCP). There are at least six possible scenarios of MSW management in Banepa: the current or baseline scenario (Scenario 1); composting with landfilling (Scenario 2); material recovery facility (MRF) recycling, composting, and landfilling (Scenario 3); MRF and anaerobic digestion (AD); composting, and landfilling (Scenario 4); MRF, composting, AD, and landfilling (Scenario 5); and, finally, incineration with landfilling (Scenario 6). Using both information from Ecoinvent 3.6 (2019) and published research articles, a spreadsheet tool based on the LCA approach was created. The impact of the recycling rate on each of the six abovementioned scenarios was evaluated using sensitivity analysis, which showed that the recycling rate can considerably decrease the life-cycle emissions from the MSW management system. Scenario 3 was found to have the least overall environmental impact with a GWP of 974.82 kg CO_2 eq. per metric ton (t), EP of 0.04 kg PO_4 eq./t, AP of 0.15 kg SO_2 eq./t, HTP of 4.55 kg 1,4 DB eq./t, ADP of −0.03 kg Sb eq./t, and POCP of 0.06 kg C_2H_4 eq./t. By adoption of MRF and biological treatments such as composting and AD, environmental impact categories such as AP, EP, HTP, ADP, POCP, and GWP can be significantly reduced. The findings of this study can potentially serve as a reference for cities in the developing world in order to aid in both the planning and the operation of environmentally friendly MSW management systems.

Keywords: environmental impacts; greenhouse gas; life cycle assessment; municipal solid waste management; Banepa municipality; Nepal; developing countries

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Citation: Shrestha, P.P.; Ghimire, A.; Dangi, M.B.; Urynowicz, M.A. Development of a Municipal Solid Waste Management Life Cycle Assessment Tool for Banepa Municipality, Nepal. *Sustainability* **2023**, *15*, 9954. https://doi.org/10.3390/su15139954

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1. Introduction

Municipal solid waste (MSW) management is one of the primary environmental challenges for developing countries. Urban growth has increased the generation of waste from residential sites as well as private and public service facilities. Despite related environmental, social, and economic problems, MSW can be used as a valuable resource that can offset future energy demands if managed via waste-to-energy pathways [1]. The organic fraction of MSW (OFMSW) can be turned into useful resources, such as fertilizers (compost and digestate) and biomethane, which can aid in achieving a circular economy [2]. However, MSW can also cause environmental deterioration and global warming as a result of the emission of anthropogenic greenhouse gases (GHGs), such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). CH_4 from solid waste disposal sites (SWDS), primarily from industrialized nations, is estimated to be between 20 and 40 million tonnes globally, which is around 5–20% of the world's total anthropogenic CH_4 emissions [3], and annual emissions of all anthropogenic GHG is between 1 to 4% of the world's total [4]. MSW management systems are complex and difficult to analyze, monitor, and measure [5]. Thus, to establish an appropriate MSW management system that minimizes the negative effects on human health and the environment, MSW management strategies require a standardized and well-described structure for evaluating environmental performance [6].

Life cycle assessment (LCA) can be used to quantify input, output, and environmental consequences over the life cycle of the project. It can be used to determine the environmental impacts of different MSW management systems, which can be useful in undertaking investment decisions for sustainable waste management infrastructures in emerging cities in low- and middle-income countries [7]. The integrated management approach, using a combination of recycling, composting, and anaerobic digestion (AD) as well as landfilling, had the lowest overall environmental impacts in terms of acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and human toxicity potential (HTP), according to an LCA conducted in Mumbai, India [7]. The incineration of MSW was shown to reduce GHG emissions but increase human toxicity potential. Another study conducted in Chandigarh, Mohali, and Panchkula, India, revealed that the open dumping of MSW had the most damaging environmental effects, while systems that included material recovery facilities (MRF), recycling, composting, and sanitary landfilling had the least damaging effects on the environment [8]. LCA was also used to analyze the effects of four different MSW management scenarios in the city of Nagpur in India. The scenarios were compared using the Gabi 8.5.0.79 database and the CML-1A impact characterization method [9]. In terms of GWP, HTP, EP, and Photochemical Ozone Creation Potential (POCP) categories, the MRF, composting, and landfilling scenarios had the least negative effects on the environment, while the composting and landfilling scenario had the most negative effects [9].

In Nepal, few studies have assessed the current and possible MSW management options from an LCA perspective [10–12]. A study considered three alternative scenarios during the LCA of the MSW management system in the city of Kathmandu [12]. Based on fuel energy consumption (FEC), GWP, EP, and AP, the three scenarios were compared in the study. Scenario 1 represented "business as usual" and consisted of collection, transportation, and landfilling; Scenario 2 included recycling; and Scenario 3 included conjunctive disposal consisting of composting and landfilling. Compared to the other scenarios, the study found Scenario 3 to have the least negative effects on the environment in terms of FEC, AP, EP, and GWP. Another LCA study assessed the environmental effects of Kathmandu's waste management employing landfill gas (LFG) recovery for electricity production and the composting of organic waste, as well as scenarios for waste disposal without LFG recovery [11]. It was determined that recovering LFG from the landfill and using the gas to generate electricity was advantageous and least damaging to the environment. In another study in the Dhulikhel municipality (Nepal), the LCA tool was used to assess the potential environmental effects of four waste treatment scenarios [10], and those with biological treatment options were found to be the most environmentally advantageous. Although there is a lack of uniformity in the usage of LCA-based studies for evaluating the environmental effects of MSW management systems, existing decision support tools (DSTs), such as EASETECH, WRATE, MSW-DST, SWOLF [13], and others, that are geared for developed nations and cities in low- and middle-income may be helpful in the selection of potential MSW management scenarios in those nations, and this would include a country such as Nepal. As such, the goal of this study is to provide a spreadsheet-based decision support tool that can be customized depending on site-specific locations in order to assess the environmental effects of various MSW management methods in Banepa, Nepal, using a gate-to-grave approach (more information about the study location is included in Section 2 below). Six MSW management scenarios were evaluated and contrasted with Banepa's current MSW management system, and, in addition, sensitivity analysis was conducted in order to ascertain the environmental implications of recycling rates.

2. Materials and Methods

2.1. Study Area and MSW Composition

Located 25 km east of Kathmandu, the Nepali capital, at an altitude of 1463 m above sea level, the Banepa municipality (27°38′ N 85°31′ E) is a small and ancient region (Figure 1). According to the recent 2021 census, it has a population of 67,690 people, and a population density of 1231 people per km^2. It comprises 14 wards, and it is a vibrant business hub of Nepal. The composition of MSW in Banepa includes 68.1% organic waste, 11.19% plastics, 9.14% paper and paper products, 1.33% glass, 1.83% metals, 1.19% textiles, 0.32% rubber and leather, and 6.9% others [14]. For resource recovery from MSW, biological treatment methods, i.e., composting and AD, may be appropriate. In addition, inorganic waste, such as plastics, rubber, leather, and wood, which have a high calorific value, could be treated using options such as incineration. The scenarios based on the different MSW management system scenarios have been considered in the study, as described in the following subsections.

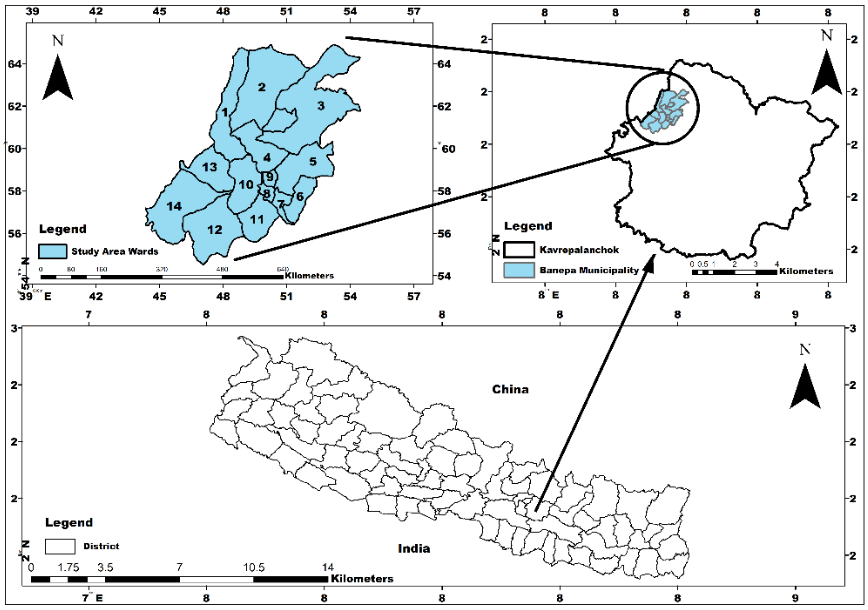

Figure 1. Map showing the location of the Banepa municipality in Kavrepalanchok district, Nepal.

2.2. Life Cycle Assessment

From waste collection until its final disposal, including waste-to-energy, emissions can be released into the air, water, and land at any time during MSW management [14]. Both human health and the environment may be harmed by these pollutants. However, environmental impact assessment tools can be used during the decision-making process in order to help manage these hazards [15]. The LCA recommended by the International Organization for Standardization (ISO): ISO 14040:2006, ISO 14044:2006 is a comprehensive method for estimating the environmental impact of the products under consideration of various waste management scenarios [16], which aids in identifying "environmental hot spots" or variables in a system that have the greatest environmental influence, thereby helping to reduce negative environmental effects as well as increase the sustainability of the system. A generic LCA consists of four steps: (i.) goal and scope definition; (ii.) inventory analysis; (iii.) assessment of potential impacts; and (iv.) interpretation of the findings in relation to the study's objectives [16,17].

2.3. Goal and Scopes of the Study

This study aimed to compare the possible environmental impacts of six MSW management scenarios, including the current or baseline conditions (i.e., Scenario 1) using LCA. The life cycle period or the scope considered was from gate-to-grave, which includes the transportation of waste to treatment facilities (open dumping, material recovery facility, composting, anaerobic digestion, and incineration) as well as the final disposal of the waste in landfills. System boundaries for the current study are shown in Figure 2 below. The mass and energy inputs and outputs from the MSW management procedures were considered within the system boundary in terms of emissions to the environment and the production of biogas, electricity, compost, and digestate. Leachate and emissions from land surfaces were not considered, and the MSW collection strategy for all scenarios within the study region was the same. The assessment of environmental impacts was performed based on inventory created in Microsoft Excel® adapted from a GHG accounting tool previously developed by [18] (provided as a supplementary file) with data from published research articles, reports, and Ecoinvent Database 3.6 (Recipe Midpoint (H) V 1.13 method), 2019, using cumulative life cycle impact assessment (LCIA) of the readily available dataset information of concerned impact categories. The proposed MSW management scenarios in Banepa were compared using the functional unit (FU) of 1 metric ton (t) of MSW.

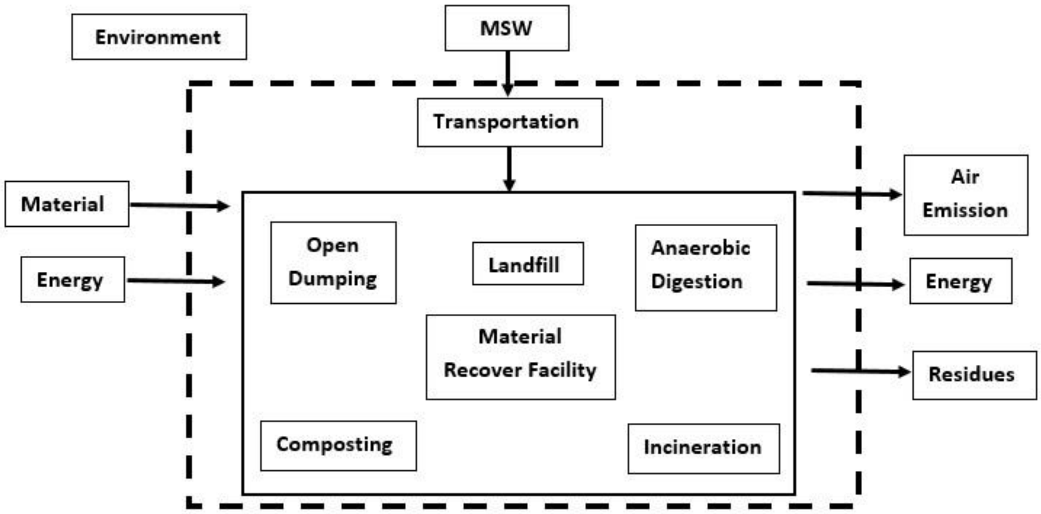

Figure 2. System boundary of the study.

2.4. MSW Management System Scenarios

There are six scenarios, including the baseline scenario for the MSW management system practices in Banepa (Figure 3).

2.4.1. Scenario 1 (S1): Baseline or Current Scenario:

This scenario is consistent with the current SWM methods, which include collection, transportation, and open dumping at the recently closed Sisdol Landfill site, which is located about 46.3 km west of Banepa. Rainwater can come into contact with disposed waste, and the moisture created by the decomposition process results in leachate. The Sisdol Landfill site came into operation in 2005 with a design life of 2–3 years, and it currently has no provision for the collection, use, and treatment of LFG or for the treatment of leachate, which poses serious environmental impacts. Although the landfill site is currently closed and has been replaced by one called Banchare Danda Landfill, it has nonetheless been used as the baseline for this study.

2.4.2. Scenario 2 (S2): Composting Combined with Landfilling

A total of 20% is designated for composting, and the remaining 80% is dumped directly into the proposed landfill site at Banepa ward 14 (Chature) for all of the MSW produced in Banepa. The site considered for the composting plant is 6 km southwest of the city center of Banepa, and there is a plan to user it as a waste disposal site [19]. The compost produced will be used as a fertilizer in the agricultural fields of Banepa.

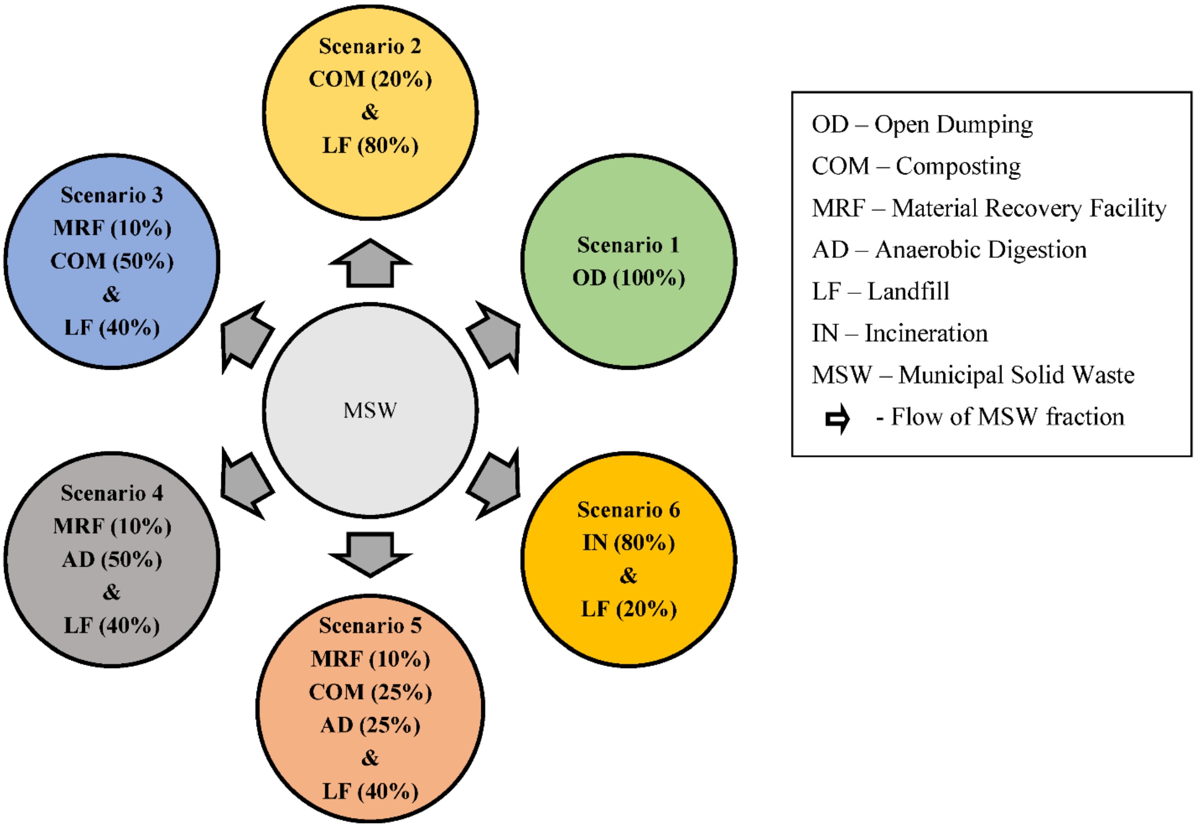

Figure 3. MSW flow in six different scenarios.

2.4.3. Scenario 3 (S3): Material Recovery Facility, Composting Combined with Landfilling

A recycling facility could support the recovery of recyclable materials, assist in the treatment of the biodegradable portion of MSW in a composting or AD plant, and support the disposal of the remaining portion at a landfill. Based on MSW composition and material flow analysis (MFA), as conducted in previous studies [15], the scenario assumes 10%, 50%, and 40% of the total MSW will be diverted to the MRF, composting, and landfilling, respectively, as treatment options. The by-products from the scenario are compost materials and recyclable materials. At the MRF, recyclable materials are separated, and they are recycled at a 20% rate. A total of 80% of the OFMSW is treated at the composting facility, and the remaining 20% is sent to the proposed landfill.

2.4.4. Scenario 4 (S4): MRF, AD Combined with Landfilling

The scenario assumes that 10% of the total MSW is diverted into MRF, that 50% goes to the AD plant, and that the rest goes to landfilling. The digestate and the recyclable materials will be used in agricultural land and recyclable industries, in that order. Biogas produced from the digester will be upgraded into bio-methane (CH_4), which can be used as a replacement for fossil fuels for heating and cooking purposes. In this scenario, it is assumed that 80% of the organic waste will be processed at the AD plant, along with 20% of the recyclable materials being recycled, and the other 20% will be disposed of in the landfill site.

2.4.5. Scenario 5 (S5): Material Recovery Facility, Composting, and Anaerobic Digestion Combined with Landfilling

This scenario incorporates both composting and AD by recycling the recyclable material at a rate of 10%, sending 50% of the organic waste to AD and composting facilities, and disposing of the remaining waste in landfills. It consists of MRF, a biological treatment facility, and also landfilling. The scenario assumes that 10% of total waste will go to an MRF, 25% to a composting facility, 25% to AD, and 40% to landfill. Biogas, compost, and digestate are some of the byproducts from this scenario.

2.4.6. Scenario 6 (S6): Incineration Combined with Landfilling

The study assumes that 80% of MSW is diverted to an incineration facility and that the remaining amount is disposed at the landfill. In this case, a continuous-type fluidized bed incinerator was contemplated to deal with the collected waste [3].

2.5. Life Cycle Inventory

A foundational step in the LCA process is the life cycle inventory (LCI). The defined functional unit provides a list of the material flows, energy flows, and environmental releases. LCI is carried out in three steps. At the beginning, it is important to identify all of the processes that take place during a product's life cycle, from the production of energy and raw materials to the disposal of waste. In addition, directly during the process or inadvertently from the existing literature and databases, data regarding the complete processes, including inputs, outputs, and emissions into the air, water, and soil, should be gathered. Finally, data is normalized to the FU defined in the assessment. According to the system boundaries considered in this study (Figure 3), the life cycle of the MSW management system and emissions to and from the environment are calculated together with inputs such as diesel as a fuel and energy and outputs such as compost, digestate, and biogas. The Asian Development Bank report [14], Banepa city office [19], published the literature, and Ecoinvent database 3.6 provided the MSW composition, the quantity, the locations of possible treatment and disposal sites, and the emission factors dataset that was utilized in our investigation. The data inventory is presented in Table 1 as two systems: (1.) the foreground system, which includes emissions of CO_2, phosphate (PO_4), sulphur dioxide (SO_2), dichlorobenzene (DB), ethylene (C_2H_4), and antimony (Sb) related to the different MSW management systems and treatment options taken into consideration in the study, and (2.) the background system. The background system comprises the foreground system's diesel and its electricity requirement as well as the generation of heat, electricity, and mineral fertilizers (compost and digestate). The following subsections provide descriptions of the various activities and unit processes in the six potential MSW management scenarios considered in the study.

Table 1. Inventory data used for six possible scenarios of MSW management systems.

Inventory for Background Data							
Inputs from Technosphere	**Unit**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Diesel	L	18.52	2.67	2.47	2.47	2.80	2.40
Electricity	kWh	-	0.54	1.35	15.25	8.30	56.00
By-Product							
Compost	T	-	0.07	0.17	-	0.08	-
Digestate	T	-	-	-	0.43	0.21	-
Biogas	m^3	-	-	-	1.50	1.50	-
Electricity	kWh	-	-	-	22.68	22.68	-
Heat	MJ	-	-	-	25.52	25.52	-
Inventory for Foreground Data							
Air Emission	Unit	S1	S2	S3	S4	S5	S6
CO_2 eq.	kg	2004.56	1930.60	974.82	948.19	969.53	1679.90
PO_4 eq.	kg	0.09	0.07	0.04	0.04	0.04	1.42
SO_2 eq.	kg	0.24	0.21	0.15	0.23	0.19	0.52
1,4 DB eq.	kg	8.15	7.04	4.55	6.58	5.57	944.56
Sb eq.	kg	−0.09	−0.07	−0.03	−0.03	−0.03	−0.05
C_2H_4 eq.	kg	0.12	0.10	0.06	0.08	0.07	−0.01

2.5.1. Transportation

The transportation units considered are "Tata LPK 407, 6–7 t GVW/4–5 t payload capacity, India". GHG emission from the use of fossil fuels by vehicles is because of the transportation of waste to and from the locations for waste treatment and disposal. The determination of emission factors from transportation assumes diesel trucks with a capacity of 4–5 t and mileage of 5 km/L.

2.5.2. Material Recovery Facility

The MRF comprises a conveyor system that is operated by electricity and diesel oil consumption followed by the manual segregation of waste. The emissions generated from the MRF process is due to energy consumption. For every tonne of waste handled, the MRF needs 0.7 L of diesel and 0.045 kWh of electricity, respectively [9]. The waste from MRF is disposed of in a landfill.

2.5.3. Composting

We consider that 68.1% of OFMSW collected from Banepa is diverted to the proposed composting facility. An open windrow composting facility has been considered in the study. The front-end loader or windrow turner, which is used for prescreening, grinding, composting, turning, post-screening, and contamination removal throughout the composting process, is a piece of heavy equipment that consumes electricity and diesel fuel. Emissions from energy consumption and the direct emissions from the composting process were both considered. The resulting compost will be applied to the ground as a soil amendment. The process assumes 1.33 L/t of MSW fuel requirement, and 2.7 kWh/t of MSW electricity requirement [20].

2.5.4. Anaerobic Digestion

It was assumed that the AD plant would process 85% of the total amount of collected OFMSW. Biogas (composed of 60% methane and 40% carbon dioxide) and digestate are the end products of AD. The digestate material can be utilized as fertilizers. For every tonne of OFMSW input, the plant was predicted to produce 850 kg of digestate [20]. It was also assumed that 120 m^3 of biogas would be produced per tonne of OFMSW, which would be upgraded into biomethane and used for cooking and transportation [21]. The potential for reducing or avoiding GWP from AD was assessed by assuming that every 1 m^3 of biogas is equivalent to 0.45 kg of liquefied petroleum gas (LPG) [22] and that each kg of LPG emits 1.67 kg of CO_2 [23].

2.5.5. Landfilling

For this study, the landfill process is modeled as an unmanaged anaerobic landfill site without LFG recovery or leachate treatment facilities on the site of the Sisdol Landfill site for Scenario 1 and on the proposed area of Banepa for Scenarios 2, 3, 4, 5, and 6. LFG produced by the breakdown of organic materials in MSW is the main source of GWP. Methane emission from the degradation of waste is dependent on several parameters, such as, to take just a few examples, the climatic condition of the landfill site (rainfall, temperature, etc.), landfill management practices, the provision of landfill cover (which facilitates the oxidation of methane), and leachate recirculation. Waste from treatment plants is entirely redirected towards landfilling. The Sisdol Landfill site was designed as a semi-aerobic landfill site and started its operation in 2005 for a 3-year design period [24], but the same site was used until very recently, when the new Banchare Dada landfill site came into operation in April, 2022 [25]. Leachate is not managed and assumed to be directly discharged into the Kolpu River, which is used as a source of domestic water by the downstream community [26]. The first-tier approach suggested in the literature is used in this study to estimate the GWP from the generation of methane from the open dumping site [3].

2.5.6. Incineration

The incineration process includes energy consumption in the form of electricity. A typical incinerator consumes 70 kWh per tonne of MSW [27]. The emission from the incineration process and electricity consumption is considered. A semi-continuous fluidized bed incinerator typically is maintained at 800–900 °C emits 0–50 kg CH_4/t and 0.067 kg N_2O/t of MSW [28].

2.6. Sensitivity Analysis and Life Cycle Impact Assessment

The effects of the six scenarios on the environment as well as their benefits were assessed using the LCA-based spreadsheet application (MS Excel) based on the earlier works in [18,29]. The six impact categories were: GWP (in kg CO_2 eq.), AP (in kg SO_2 eq.), EP (in kg $PO_4{}^{3-}$ eq.), ADP (in kg Sb eq.), HTP (in kg 1,4-DB eq.), and POCP (in kg C_2H_4 eq.). Sensitivity analysis was used to determine how changing the rate of recycling or diverting waste to the MRF will affect the various environmental impact categories. The percentage of recycled materials recovered from the waste is regarded as the recycling rate. The reduction of virgin material production, waste reduction, resource recovery, and the utilization of materials are the benefits of recycling, considering that they are all important parameters in MSW management. In this study, recyclable materials such as paper, plastics, glass, metals, rubber and leather, and textiles are all taken into account. In each of the scenarios, the effects of the various recycling rates, ranging from 10% to 70%, were examined. The individual electricity technologies present in the grid also have significant impacts on the results, but they are kept fixed in this study and are not considered for sensitivity analysis.

3. Results and Discussion

3.1. Environmental Impacts of MSW Management Scenarios

MSW generation from Banepa is 8.56 t/day, of which 4.5 t/day is collected with a collection efficiency of 52.5%, and the average waste generation is 344 g/capita/day [14]. Uncollected LFGs, incineration, transportation, biological treatment processes, and energy production are the main activities that cause GHG emission. Preventing waste from decomposing in landfills is the main activity that reduces GHG emission. Additionally, the use of biogas in place of LPG, the use of compost and digestate instead of inorganic fertilizers, the sequestration of carbon by the compost and the digestate, and the avoidance of the generation of electricity and fuel using AD all reduce GHG emission. The GHG emission and the benefits of all of the scenarios, including the baseline one, are shown in Table 2. It was found that Scenario 4 had the maximum GHG benefit, and the reason for this is that a greater proportion of organic waste is redirected to the anaerobic digesters, which create biogas that replace fossil-based LPG as a cooking fuel in addition to the organic fertilizer produced during the composting process. Furthermore, GHG benefits can be observed in Scenarios 2, 3, and 5, but, comparatively, less than in Scenario 4.

Table 2. Activities contributing to GWP and GWP benefits for the six SWM scenarios (S1–S6).

Activities Contributing to GHG's	Unit	S1	S2	S3	S4	S5	S6
Uncollected Landfill gas	kg CO_2 eq./t	1994.57	1928.48	964.24	964.24	964.24	482.12
Transportation		10.00	1.30	1.30	1.30	1.30	1.30
Composting		-	6.12	22.33	-	11.17	-
Anaerobic Digestion		-	-	-	42.00	30.06	-
Incineration		-	-	-	-	-	1196.14
Electricity consumption (Treatment option)		-	0.00	0.01	0.09	0.05	0.34
Diesel Consumption (Treatment Option)		-	0.72	1.98	0.19	1.09	-

Table 2. *Cont.*

Activities Causing Benefits	Unit	S1	S2	S3	S4	S5	S6
Replacing LPG gas by biogas	kg CO_2 eq./t	-	-	-	44.96	22.48	-
Avoidance of inorganic fertilizer (compost)		-	1.40	3.49	-	1.75	-
Avoidance of inorganic fertilizer (digestate)		-	-	-	9.21	4.61	-
Carbon sequestration from digestate application		-	-	-	3.40	1.70	-
Carbon sequestration from compost application		-	4.62	11.55	-	5.78	-
Avoidance from electricity generation (AD)		-	-	-	0.14	0.14	-
Avoidance from fuel consumption (AD)		-	-	-	1.92	1.92	-
Total GHG's contribution (kg CO_2 eq./t)		**2004.56**	**1930.60**	**974.82**	**948.19**	**969.53**	**1679.90**

The temperature rise brought on by the GHGs, such as CO_2 and CH_4, N_2O, and hydrochlorofluorocarbons (HCFCs), is responsible for global warming. MSW treatment produces both biogenic and fossil CO_2 and biomethane, with the biogenic CO_2 and CH_4 released by the decomposition of the biodegradable portion of MSW and the non-biogenic CO_2 produced by burning non-biodegradable materials (including plastics, textiles, and rubber and leather). Although biogenic CO_2 can be assumed to have a zero impact factor (i.e., it does not contribute to global warming), methane is a much stronger greenhouse gas [3]. The baseline scenario has the highest GWP (2004.56 kg CO_2/t), which is caused by high fossil CO_2 and biomethane emission, by a lack of waste segregation, and by an LFG control mechanism. Nevertheless, GWP can be significantly decreased by introducing MRF. Table 3 indicates that Scenario 3 had the lowest GWP (974.82 kg CO_2/t) due to the composting process, which reduces the amount of biogenic methane that is produced. Composting with landfilling has been shown to have the highest GWP (1259.69 kg CO_2 eq./t), while composting with landfilling and MRF has the lowest GWP (721.79 kg CO_2 eq./t) [7]. Landfilling of 1 kg of MSW (average composition of MSW in European countries) has an impact of GWP equivalent to 1.08 nanograms (ng) which seems to be lower than determined in this study [30]. Another study has reported the higher contribution of GWP (37%) when seven impact categories were determined for the landfilling scenario of food catering waste [31]. This is in agreement with our results in Scenario 1. One tonne of OFMSW can produce 0.33 t of compost [20], and 1 tonne of compost application can sequester 70 kg of CO_2 [32]. Similarly, 1 tonne of OFMSW can produce 0.85 t of digestate [19], and 1 tonne of digestate can sequester 8 kg of CO_2 [33]. This information was used in the estimation of the impacts and the offsets in the six different scenarios.

Table 3. Summary of results on life cycle impacts for different scenarios.

Scenario–MSW Management Systems	Acidification Potential, AP (kgSO_2 eq./t)	Eutrophication Potential, EP (kg PO_4 eq./t)	Global Warming Potential, GWP (kg CO_2 eq./t)	Human Toxicity Potential, HTP (kg 1,4-DB eq./t)	Abiotic Depletion Potential, ADP (kg Sb eq./t)	Photochemical Oxidation, POCP (kg C_2H_4 eq./t)
Scenario 1 (Baseline)	0.24	0.09	2004.56	8.15	−0.09	0.12
Scenario 2 (Co-LF)	0.21	0.07	1930.60	7.04	−0.07	0.10
Scenario 3 (MRF-Co-LF)	0.15	0.04	974.82	4.55	−0.03	0.06
Scenario 4 (MRF-AD-LF)	0.23	0.04	948.19	6.58	−0.03	0.08
Scenario 5 (MRF-Co-AD-LF)	0.19	0.04	969.53	5.57	−0.03	0.07
Scenario 6 (MRF-In)	0.52	0.04	1679.90	944.56	−0.05	−0.01

During the compost process, acidifying gases such as NO_x and SO_x are released into the atmosphere, which is the primary cause of acidification. It has been discovered that NO_x has a relatively stronger acidification effect than SO_x, which may be due to the presence of mineral fertilizers and the features of MSW [9]. Scenario 6 had the highest AP (0.52 kg SO_2 eq./t), which significantly increases acidification by transforming the sulfur and nitrogen content of incinerated waste into acidic gases such as SO_x and NO_x. Moreover, the processes of composting and landfilling have the potential to release gases such as N_2O and NH_3. Scenario 3 had the lowest AP (0.15 kg SO_2 eq./t) because there are lower sulfur and nitrogen-containing chemicals involved in and oxidized during the composting and MRF processes. The study shows that MRF and incineration were found to have the maximum acidification impact (0.65 kg SO_2 eq./t), while open dumping with a bioreactor landfill has the least acidification potential (0.12 kg SO_2 eq./t) [7]. One study reported composting with landfilling had the least AP (0.19 kg SO_2 eq./t), and that MRF and AD with a landfilling scenario had the highest AP (0.68 kg SO_2 eq./t) [7].

Nutrients such as ammonia, nitrogen oxide, and phosphate are responsible for eutrophication. Due to the significant quantity of nitrogen and phosphorous emissions from the landfill site, Scenario 1 had the maximum eutrophication impact (0.09 kg PO_4^{3} eq./t). The biological processes taking place inside the disposal site generate nitrogen and phosphorous gases, which can dissolve in leachate and have greater negative effects on the environment. Scenario 3 and Scenario 4 showed the least eutrophication impact (0.04 kg PO_4^{3-} eq./t) due to source separation. Research has also shown that open dumping with a bioreactor landfill has a high EP (0.47 kg PO_4^{3-} eq./t) [7]. Due to the presence of impermeable synthetic liners and leachate treatment MRF, composting and landfilling have been shown to have the lowest EP [7]. A unit kg of MSW is reported to have 0.25 ng EP for landfilling [30].

The findings in Figure 4 are based on the six impact categories (GWP, AP, EP, HTP, ADP, and POCP), respectively. Scenarios 3, 4, and 5 are also shown to have the highest abiotic depletion potential (−0.03 kg Sb eq./t), resulting in the over-extraction of non-fossil fuels (renewable resources) compared to the other scenarios. Scenario 1 had the least ADP (−0.09 kg Sb eq./t). For landfilling, a unit kg of MSW had 0.13 ng of ADP [30]. Human toxicity is caused by the emission of pollutants, such as particulate matter, SOx, NOx, and heavy metals. Scenario 6 (incineration combined with landfilling) resulted in the highest HTP (944.56 kg 1,4 DB eq./t) due to the high emissions of heavy metals, SOx, and NOx during the combustion process. Out of the possible outcomes, Scenario 3 had the lowest environmental impact (4.55 kg 1,4 DB eq./t), which suggests that composting and material recovery have less of an influence on toxicity-causing agent emissions than landfilling. The chemical interactions between NOx, carbon monoxide, and VOCs in the presence of sunlight produce tropospheric ozone and asthma, and other respiratory issues may also arise from low levels of ozone exposure [6]. Scenario 1 possessed the maximum POCP (0.12 kg C_2H_4 eq./t), where diesel usage, methane production, and NOx emissions were the major contributors. In addition, a large amount of photochemical oxidant precursors (VOCs, CO_2, NO_2, NOx, and fine particles) can be released during the process. Scenario 6 had the least POCP (−0.01 kg C_2H_4 eq./t).

Energy consumed in landfills and open dumping activities, such as waste spreading and leachate treatment, waste disposal practice including compaction, and application of soil cover, were not accounted for in this study due to the unavailability of reliable site-specific data.

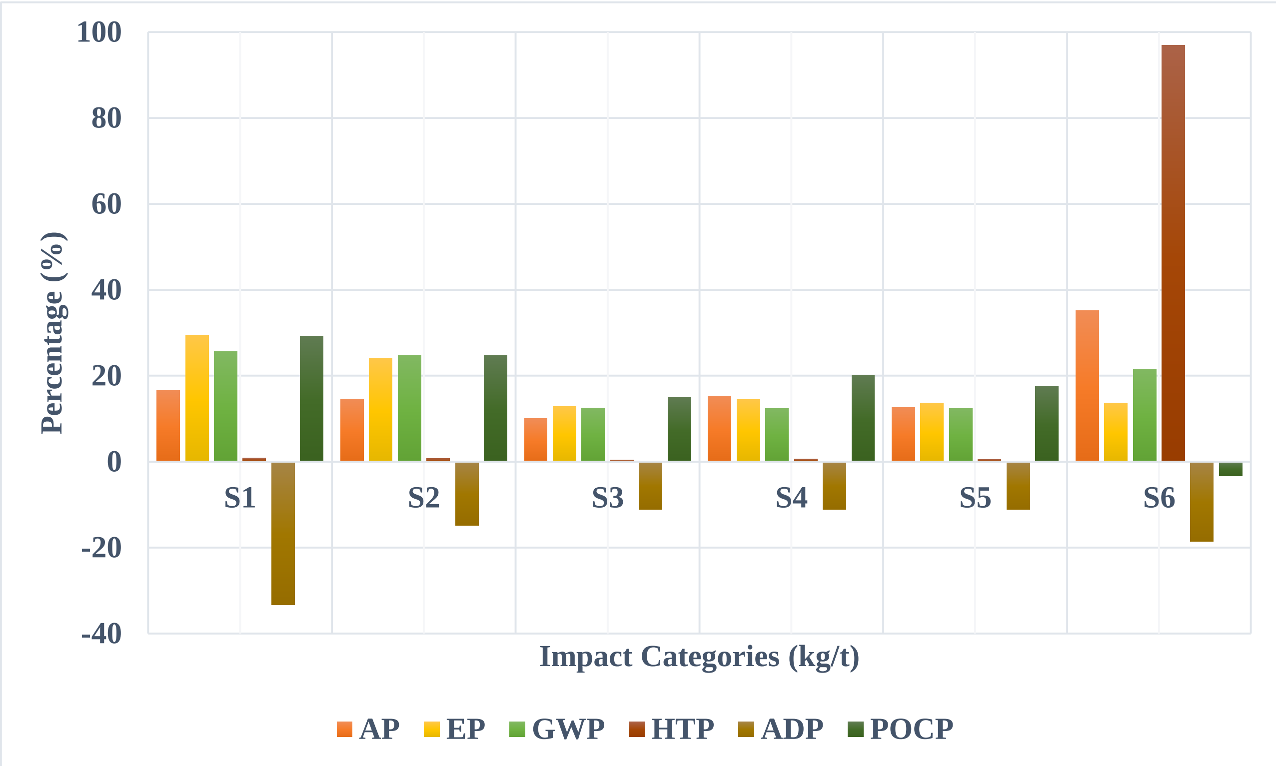

Figure 4. LCA characterization of considered environmental impact categories.

3.2. Sensitivity Analysis

The result of the sensitivity analysis based on increasing the recycling rate from 10% to 70% is included in Figure 5. The analysis showed that MSW for landfilling and biological treatment, including composting and AD, vary from 15 to 45% as recycling ranged from 10 to 70%. This also indicates that the environmental effects of the sensitivity analysis results are caused by the variation in the recycling rate (variation in the quantity of recyclables such as paper, plastics, metals, textiles, etc. quantified in terms of percentage) in scenarios, i.e., Scenario 3, 4, and 5. The change in recycling rate and the effects on the environment are inversely correlated as in the previous studies [7,9]. As a result, it was determined that the introduction of MRF would increase the environmental advantages of recycling. Research has also shown that combining MRF, composting, and landfilling results in increased environmental benefits.

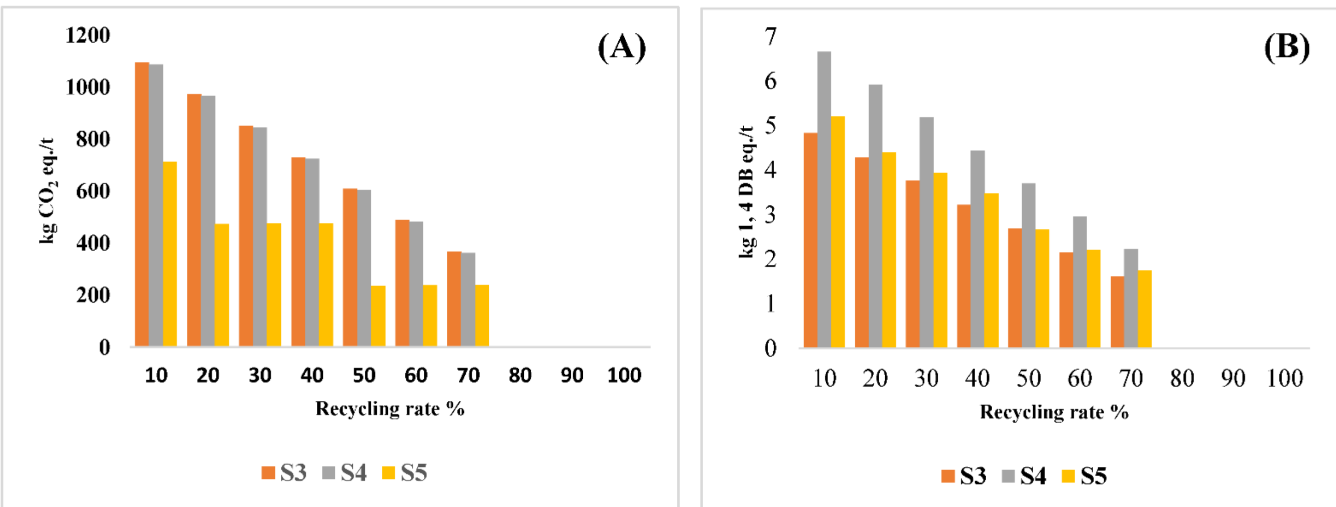

Figure 5. *Cont.*

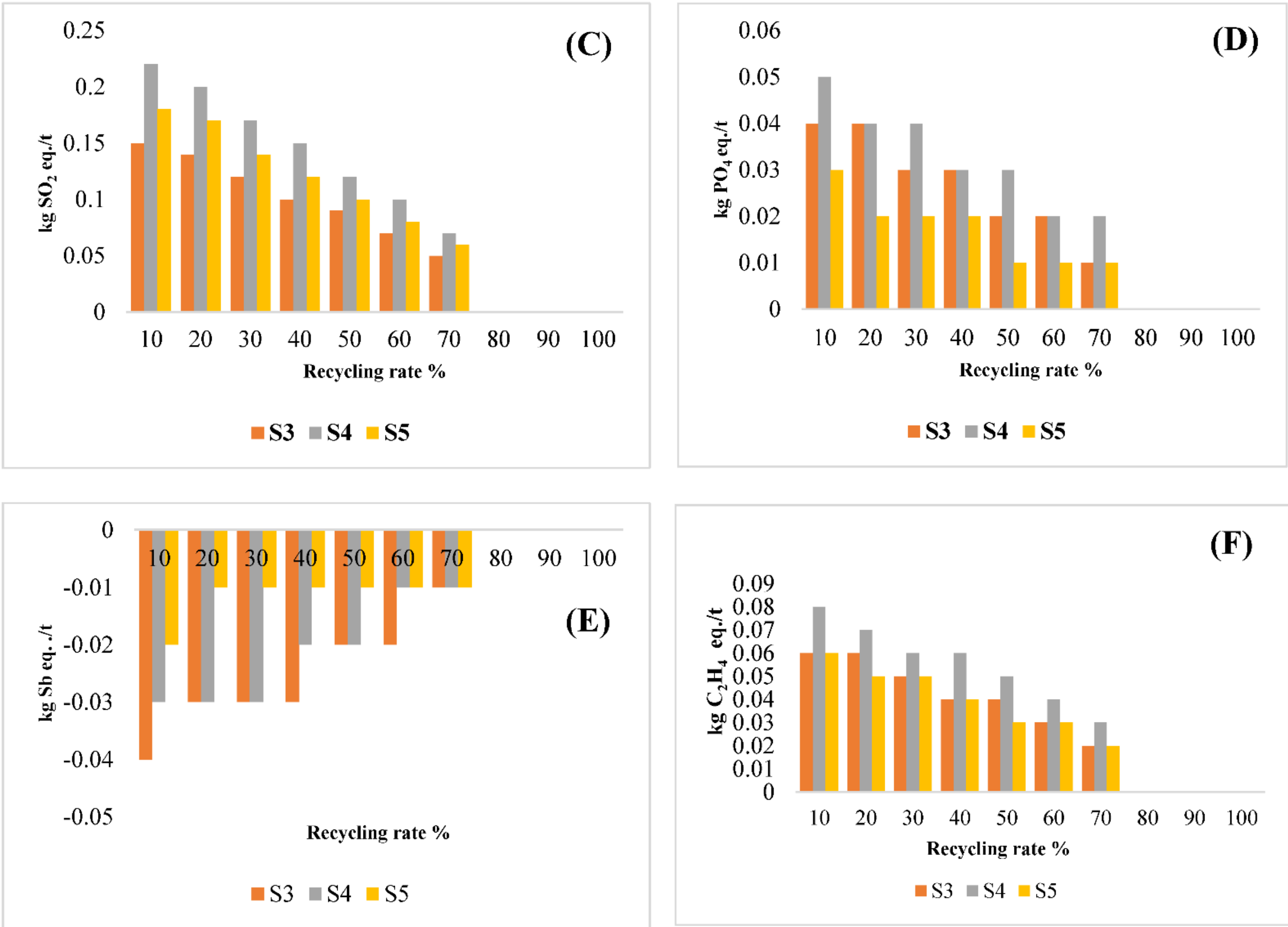

Figure 5. Sensitivity analysis of proposed scenarios (Scenarios 3, 4, and 5) in recycling rate in terms of GWP (**A**), HTP (**B**), AP (**C**), EP (**D**), ADP (**E**), and POCP (**F**) per tonne (t) of waste.

4. Conclusions and Recommendations

This study developed and successfully tested the LCA-based MSW management decision support spreadsheet tool for the city of Banepa city in Nepal in order to evaluate the best suited and most sustainable MSW management systems that have the least detrimental environmental impacts. Among the six proposed scenarios, Scenario 3, which involved the material recovery facility and composting combined with landfilling, was found to be the least impactful MSW management scenario in terms of the environmental impact categories. Scenario 3 had GWP of 974.82 kg CO_2 eq./t, EP of 0.04 kg PO_4^{3-} eq./t, AP of 0.15 kg SO_2 eq./t, HTP of 4.55 kg 1,4 DB eq./t, ADP of −0.03 kg Sb eq./t, and POCP of 0.06 kg C_2H_4 eq./t. Scenario 4 had the least GWP of 966.31 kg CO_2 eq./t, EP of 0.04 kg PO_4^{3-} eq./t, AP of 0.23 kg SO_2 eq./t, HTP of 6.58 kg 1, 4 DB eq./t, ADP of −0.03 kg Sb eq./t, and POCP of 0.08 kg C_2H_4 eq./t. Scenario 4 had maximum GHG benefit as it had the lowest GWP. This was due to a greater proportion of organic waste redirected into anaerobic digesters creating biogas and the replacement of fossil-based LPG as a cooking fuel in addition to the organic fertilizer produced. However, Scenario 4 had substantially higher HTP than that of Scenario 3 and 5. Scenario 3 seems to be the best scenario for MSW management for the city of Banepa, and it had the least environmental impacts in terms of AP, EP, HTP, and POCP, which are also relatively favorable from both health and environmental perspectives. The baseline or existing scenario was shown to have the most severe and detrimental environmental effects. The LCA of MSW management systems shows that emission from uncollected landfill gas poses the greatest potential threat to the environment. Sensitivity analysis also showed that the recycling rate can considerably decrease life-cycle emission, and that recycling MSW was the most desirable option for the sustainable management of waste. Environmental impact categories, such as AP, EP, HTP, ADP, POCP, and GWP, can also be significantly reduced by the adoption of MRF and biological treatments, such as composting and AD. The outcomes of the study can serve as a reference for similar emerging cities to aid in planning effective MSW management systems and improving their operation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15139954/s1, Waste Management Decision Support Tool. References [18,29] are cited in the supplementary materials.

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Abbreviations

AD	Anaerobic Digestion
AP	Acidification Potential
CH_4	Methane
CO_2	Carbon Dioxide
C_2H_4	Ethylene
CFCs	Chlorofluorocarbons
COM	Composting
DB	Dichlorobenzene
DSTs	Decision Support Tools
EP	Eutrophication Potential
FEC	Fuel Energy Consumption
FU	Functional Unit
GHGs	Greenhouse Gases
GWP	Global Warming Potential
HTP	Human Toxicity Potential
ISO	International Organization for Standardization
IN	Incineration
kWh	Kilowatt Hour
Kg	Kilogram
Km/L	Kilometer per Litre
L	Litre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LFG	Landfill Gas
LF	Landfill
m^3	Cubic Meter
MFA	Material Flow Analysis
MSW	Municipal Solid Waste
MRF	Material Recovery Facilities
MJ	Megajoule
Ng	Nanogram
N_2O	Nitrous Oxide
OD	Open Dumping
OFMSW	Organic Fraction of Municipal Solid Waste
POCP	Photochemical Ozone Creation Potential
PO_4	Phosphate
Sb	Antimony
SO_2	Sulphur Dioxide
SWDS	Solid Waste Disposal Sites
S1	Scenario 1
S2	Scenario 2
S3	Scenario 3
S4	Scenario 4
S5	Scenario 5
S6	Scenario 6
t	Metric tonne
VOCs	Volatile Organic Compounds

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An Assessment of the Impact of Land Use and Land Cover Change on the Degradation of Ecosystem Service Values in Kathmandu Valley Using Remote Sensing and GIS

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Abstract: Land use and land cover (LULC) robustly influence the delivery of the ecosystem services that humans rely on. This study used Kathmandu Valley as a study area which is a fast-growing and most vulnerable city to climate change. Remote sensing and GIS methods are the most significant methods for measuring the impact of LULC on the ecosystem service value (ESV). The satellite-based dataset was used for quantitative assessment of the LULC and ecosystem service value for 10-year intervals from the year 1989 to 2019. The result revealed that the area of forest cover, cropland, and waterbodies decreased by 28.33%, 4.35%, and 91.5%, respectively, whereas human settlement and shrubland increased by more than a hundred times and barren land by 21.14% at the end of the study period. This study found that Kathmandu valley lost 20.60% ESV over 30 years which dropped from USD 122.84 million to USD 97.54 million. The urban growth and extension of agricultural land to forest cover areas were found to be contributing factors for the reduction in ESV of Kathmandu valley. Cropland transformed into shrubland, bringing about an increase in ESV of some areas of the study region. In conclusion, the aggressive increase in population growth with inadequate urban planning and fragmentation of farmlands influenced the ESV of Kathmandu valley.

Keywords: ecosystem service value; land cover; remote sensing; urbanization; Kathmandu Valley

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1. Introduction

Changes in land use and land cover have been accompanied by a perceived rise in the availability of a diverse variety of ecosystem services (ES) for both local and global consumers. Recreation and ecotourism, biodiversity habitat provision, soil conservation, carbon storage, resource availability, and water quality are all examples of ecosystem services [1]. ES is particularly necessary for those who rely on subsistence livelihoods, which comprise about one-fifth of the world's population [2]. Human survival is entangled with a variety of natural resources and ecosystems, including agriculture, forestry, and water, which provide a wide range of valuable services to human society at all times [2]. Human interference has had a significant impact on land cover types for many years [3–5], and this has resulted in significant changes in the amount and capacity of ecosystem services provided [6–8]. The large-scale alteration in LULC due to significant human actions and urbanization directly impacts socio-economic development and environmental sustainability [9–13]. As a city grows, it may improve the livelihood and wages of people but also has substantial environmental consequences. On local, regional, and global scales, land conversion for urbanization is one of the most prevalent drivers of ecosystem damage, altering the earth's landscape and potentially affecting vital ecosystem services in the long term [14]. The transformation of numerous land covers into built-up areas is the specific factor for the alteration of surface temperature, trace gases, aerosols, and changes between the ground surface and the atmosphere [15]. As more than half of the world's population is already living in cities, and is expected to continue [16], these environmental effects are predicted to worsen in the mid-twenty-first century.

The pattern of converting natural landscapes into urban settlements has changed the confined environment, which is hotter than its surroundings [17–20]. The major drivers for the conversion of arable land to urban sprawl [21] are rapid population growth, urban expansion, and socio-economic development despite provisional services being incredibly important for the environment and human well-being [22–24]. Kathmandu valley's haphazard and unplanned urbanization has degraded the urban environment, increased urban poverty, and exposed the valley's rising urban population to multiple hazards such as flooding, drought, air pollution, etc. Despite rapid urbanization in Kathmandu valley, the Government of Nepal (GoN) has implemented limited measures to improve the ecological environment. There are only a few specific projects based on water-related services rather than conserving forest areas and preserving fertile lands. Though the GoN has recognized and integrated ecosystem services into national development plans, there are still major losses in ESV due to a lack of proper planning and monitoring for natural capital management. A deeper understanding of LULC was analyzed with their drivers and effects on ecosystem services, as well as to comprehend landscape patterns and changes. The quantification of ecosystem services into monetary value would provide evidence to decision-makers to understand the potential cost of ecosystem restoration. The remote sensing and Geographical Information System (GIS) tools practiced in measuring land use cover change provide a new way for ecosystem service studies [25,26]. Satellite images have been used as the primary data sources for detecting urban expansion due to long-term data availability at the required spatial and temporal distribution. The study of land cover change and its effects on the environment of urban areas is critical for long-term development and planning to achieve an efficient balance between society, national economics, and the environment [27–29]. While it is demonstrated that the measurement of ESV with scientific studies using high-resolution images and GIS tools can reveal some remarkable pieces of information on the degradation of the ecosystem and environment, no such studies have been conducted in recent years for Kathmandu valley. There is a clear need for a detailed spatiotemporal analysis of land cover and its impact on ESV for a rapidly urbanizing area such as Kathmandu valley. The main objective of this study is to (a) analyze the changes in the LULC pattern and its impact on the degradation of the ESV of Kathmandu valley and (b) provide guidance and information for the management of future expansion of urban settlement and sustainable use of land resources.

2. Materials and Methods

2.1. Study Area

Kathmandu valley lies in the central part of Nepal. It covers three districts Bhaktapur, Kathmandu, and Lalitpur. Kathmandu valley lies between latitudes 27°30′ N to 27°50′ and longitudes 85°10′ E to 85°31′ E, with an area covering 933.73 sq km (Figure 1). It is a bowl-shaped area surrounded by a mountain with an elevation ranging between 1900–2800 m above sea level (masl). The average height of Kathmandu valley is 1300 masl Kathmandu valley lies in the sub-tropical region experiencing average temperature and annual humidity of 24 °C [30] and 75%, respectively, due to changes in physiology and climatic conditions [25]. The mean annual rainfall of Kathmandu valley is 1600 mm, with nearly 80% occurring during the monsoon season [31]. It is an important site for a study of the impact of LULC on ecosystem services due to urbanization, air pollution, and environmental degradation. The key problem for the study area's future clash between economic development and environmental protection as Kathmandu has been named one of the world's 15 most vulnerable cities by the International Institute for Environment and Development (IIED) [32].

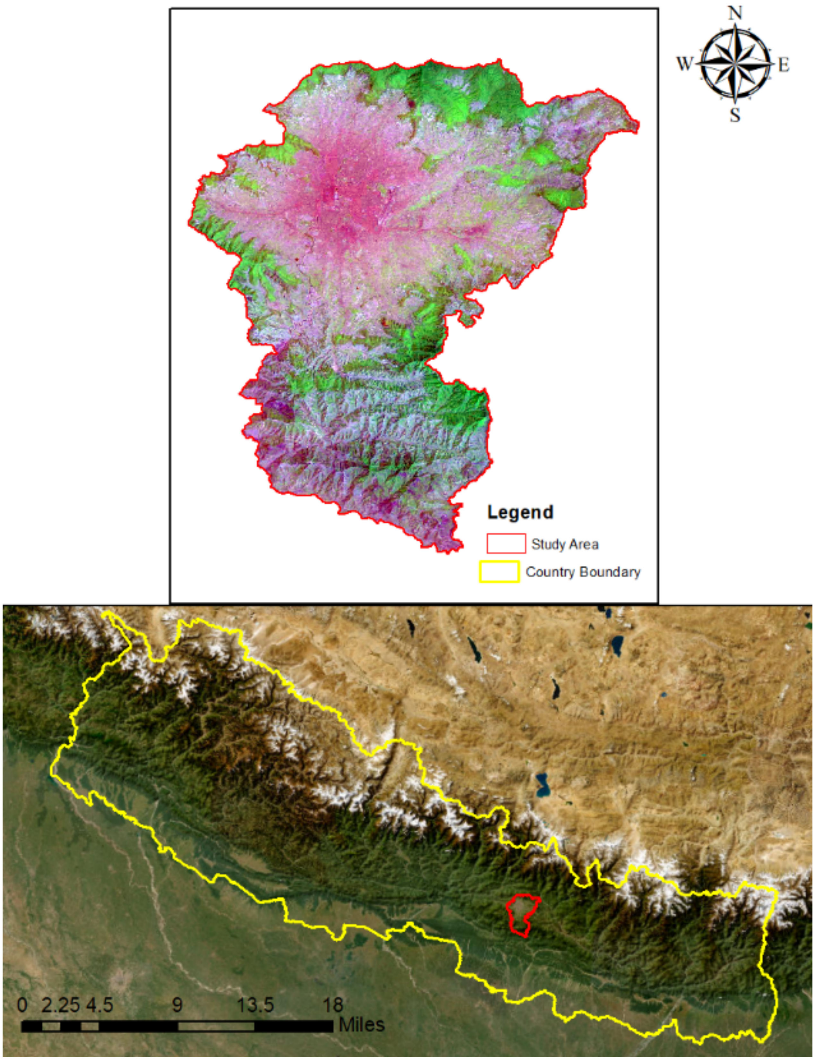


Figure 1. Study Area Location.

2.2. Data Sources

In this study, 1989 is chosen as the earliest year for the data analysis based on the low image resolution and data availability of satellite images and the quality of the existing reference dataset. Data are available through the year 2019. The geometrically corrected data of Landsat Level 1 products were downloaded from the United States Geographical Survey (USGS) [33]. The study followed 10-year intervals to visualize the difference in LULC dynamics.

Spatial data were acquired at a resolution of 30 m from the Landsat-5 Thematic Mapper (TM) for the years 1989, 1999, and 2009, and Landsat-8 Operational Land Imager (OLI) images were used for the year 2019. More details of the acquired data are shown in Table 1. The acquired data period was selected for the post-monsoon period (October to December), which mostly has vegetation green to semi-evergreen [34] and free from cloud cover [35]. After downloading data from the USGS source was pre-processed by extracting the study area, radiometric and atmospheric correction.

Table 1. Landsat Data Used for the Study.

Landsat	Path/Row	Spatial Resolution	Acquired Year
Landsat 8 OLI/TIRS	141/41	30m	18 December 2019
Landsat 5 TM	141/41	30m	28 December 2009
Landsat 5 TM	141/41	30m	27 October 1999
Landsat 5 TM	141/41	30m	2 December 1989

2.3. Image Pre-Processing and Classification

To avoid data error or tampering and to establish a direct link between data and biophysical processes, satellite images have to be preprocessed. Each Landsat image is an L1T product, and geometric corrections were performed during data preprocessing. This study used atmospheric and radiometric correction procedures in ArcGIS 10.3 for removing atmospheric noises and surface reflectance caused by the earth's rotation [36]. All of the images were processed for radiometric calibration (digital number (DN) to top-of-atmosphere (TOA)) and atmospheric corrections [37,38]. The atmospheric correction eliminated the effect of atmospheric absorption and scattering, which gives true surface reflectance data [39,40]. As the band composition is very important for LULC classification and every Landsat sensor has a different band, those bands were carefully composited into one layer. The framework of this study is shown in Figure 2.

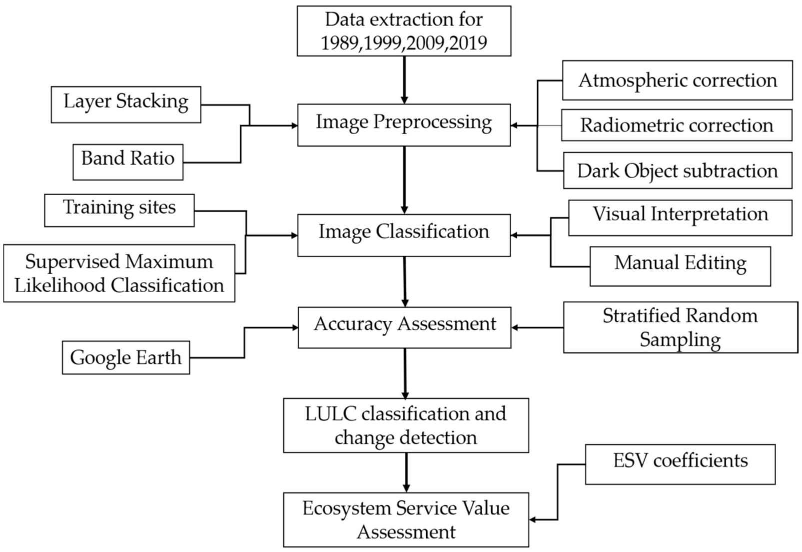


Figure 2. The methodology used in the study.

In this study, the LULC classification uses a supervised classification method. In supervised classification [41], Maximum Likelihood Classification(MLC) is the most widely used [42–44] parametric algorithm, and it gives better classification results for quantitative analysis [45]. At first, a number of signatures of each land class were generated for data training. These signatures were grouped manually into predefined land classes using simple random sampling, high-resolution Google Earth, and subject-matter expertise and familiarity with the study area. For RS image classification, the quality and quantity of selection of training samples are largely related to the accuracy of overall classification [46]. In order to get a better classification result, more than 15 samples of each land cover type were selected for training data [47]. Then supervised classification was carried out of all Landsat image using MLC. Based on the degree of similarity and properties of pixels, MLC is categorized into one of the land class groups. In this study, six land cover types were selected based on the land use types and intensity of land use changes. Table 2 shows the major land cover types and their description of their characteristics in the study area. The descriptions of land cover types in the table below describe the nature and characteristics of land classes in the study area.

Table 2. Major Land Use and Land Cover types.

Land Cover Types	Description
Forest Cover	A land dominated by trees, including natural woodlands and community plantations.
Shrubland	Bushes, grasslands, shrub cover, and degraded forests
Barren land	Areas of silt and sand with very little or no vegetation, such as the shores of rivers.
Cropland	Farmlands and cultivable lands, including seasonal croplands
Built-up Area	Residential, commercial, industrial, roads, and construction site
Waterbody	All types of water bodies such as rivers, ponds, and lakes

2.4. Accuracy Assessment

The final and most important step during the land cover type classification in the remote sensing data process is accuracy assessment or validation [48]. Accuracy assessment is an important activity due to the possibility of inaccuracy in the Landsat data. It compares the produced data by the user with the real ground truth data. The accuracy of classified land cover classes was measured using an error matrix [49], user accuracy, producer's accuracy, overall accuracy [48], and Kappa coefficient [10] to verify the precision and error of the images by comparing them to actual ground truth points [50]. The accuracy assessment of land cover data was carried out using the generally accepted stratified random sampling method. Google Earth provides high-resolution satellite photos at no cost, which are critical references for validating the LULC classification [42,51–54]. In order to understand the accuracy of classified land classes, nearly 900 samples of actual ground truth data of each class were taken randomly and compared to classified land classes. The number of samples of each class sample depended on the area of the land class, varying between 15 to 900. First of all, an accuracy assessment point was created in classified data in GIS which was exported to Google Earth (Google Earth Pro version 7.3). Each random point was verified by comparing it with the ground truth for accuracy assessment. For this study, Google Earth images from December 2009 and 2019 were used as the reference for classified land classes of 2009 and 2019, respectively, and a 1:25,000 scale topographic map as a reference for classified land classes of 1989 and 1999. An error matrix was generated using reference points.

The overall accuracy of the classified image is determined by comparing how each satellite image cell is classified to the definite land cover conditions acquired from the actual land cover. The likelihood of a categorized pixel matching the land cover type of its corresponding real-world place is measured by the user's accuracy [41,55]. Producer accuracy is a measure of how well real-world land cover types can be classified [56]. The kappa coefficient is a frequently used method for agreement with classified and actual land cover and is calculated using equation 1 shown below for each land cover classification [49]. The kappa coefficient value ranges from-1 to +1; the higher the value, the greater the agreement [57].

$$\text{Kappa Coefficient} = \frac{\sum_{i=1}^{m} x_{ii} - \sum_{i=1}^{m} x_{ii}(A_i C_i)}{n^2 - \sum_{i=1}^{m} x_{ii}(A_i C_i)} \quad (1)$$

where n is the total number of stratified random samples taken, x_{ii} gives the number of samples in actual class i, A_i is the total number of actual ground truth samples associated with class i, C_i represents the total number of the classified sample belonging to class i, m is numbers of rows and columns in the error matrix.

2.5. Ecosystem Service Value Assessment

The various direct and indirect methods can be used for estimating the value of ecosystem services. Using a supply and demand analysis of the sum of consumer and producer surplus (or the price times quantity for certain ecological services), Costanza et al. calculated the value per unit area of each ecosystem service for diverse ecosystems [58]. To estimate the global ESV, 17 ecosystem services from 16 biomes were categorized [32,58]. Xie et al. [34] estimated the ESV per unit area of the different land types in the Tibetan Plateau based on Costanza's global ESV [35]. For the analysis of ESV in the Koshi river basin, Zhao et al. [59] used the modified value calculated by Xie et al. As the Kathmandu valley is in the same river basin with similar climatic and topographical features, this study followed the adjusted price value coefficient of the ecosystem by Xie et al. [50], which is shown in Table 3.

Table 3. ESV coefficient for different land cover types given by Xie et al [34].

Land Cover Types	ESV (USD/ha/year)
Forest Cover	2168.84
Shrubland	1089.19
Barren land	0.00
Cropland	699.37
Built-up Area	0.00
Waterbodies	6552.97

The ecosystem service value is calculated for six different land cover types, which are represented as the forest cover for dense forests, shrubland for light forest cover shrubs and grasslands, cropland for cultivated areas, barren land for dry and unused land, built-up area for urban settlements and water body for water resources. The ESV coefficient for the built-up area and the barren area was considered zero as the urban area is responsible for heat generation and erosion generating large amounts of heat undesirable for the residents and environment and causing loss of habitats [23,60]. The total ecosystem service value of each classified land cover was obtained by multiplying the value coefficient with the area of each land type [59,60].

$$ESV = \sum(A_i \times VC_i) \quad (2)$$

where ESV is the total estimated ecosystem service value of each land type, A_i denotes the area of each land cover type in ha, and VC_i represents the ecosystem value coefficient in USD/ha/year.

3. Results

3.1. Land Use and Land Lover Accuracy Assessment

According to the results of the accuracy assessment for the land cover classification (Table 4), the user's accuracy and producer's accuracy were found to be 94.78 and 96.19 for 1989, 95.93 and 94.44 for 1999, 94.44 and 94.72 for 2009 and 84.27 and 88.72 for 2019 respectively. The overall accuracy was 94.86 for 1989, 93.61 in 1999, 95.18 for 2009, and 91.08 for 2019. The kappa coefficients were found within the almost perfect agreement [61] of 0.93, 0.91,0.93,0.87 for 1989, 1999, 2009, and 2019 respectively. The UA and PA for each land class, OA, and kappa coefficient are shown in Table 5.

Table 4. Confusion matrix of land classification in 2019.

LULC Class	Forest Cover	Shrubland	Barren Land	Cropland	Built-Up Area	Water Bodies	Total
Forest Cover	255	2	0	20	1	0	278
Shrubland	3	67	0	22	1	0	93
Barren land	0	0	13	3	3	0	19
Cropland	0	1	2	312	13	1	329
Built-up Area	0	0	0	1	147	3	151
Waterbody	0	0	0	0	3	13	16
Total	258	70	15	358	168	17	886

Table 5. Assessment Accuracy on LULC Classification for 1989, 1999, 2009, and 2019.

LULC Class	1989		1999		2009		2019	
	User's	Producer's	User's	Producer's	User's	Producer's	User's	Producer's
Forest Cover	98.00	98.49	96.46	96.95	98.38	98.70	91.73	98.84
Shrubland	86.96	95.24	95.95	98.61	84.62	100.00	72.04	95.71
Barren land	100.00	100.00	100.00	78.95	100.00	96.00	68.42	86.67
Cropland	92.20	93.10	89.45	94.25	93.10	94.08	94.83	87.15
Built-up Area	97.22	90.32	93.7	91.39	96.97	88.89	97.35	87.50
Waterbody	94.29	100.00	100.00	90.91	93.55	90.63	81.25	76.47
Overall Accuracy (%)	94.86		93.61		95.18		91.08	
Kappa Coefficient (%)	93.26		91.51		93.31		87.57	

All Users and Producers indicate accuracy is in percentage.

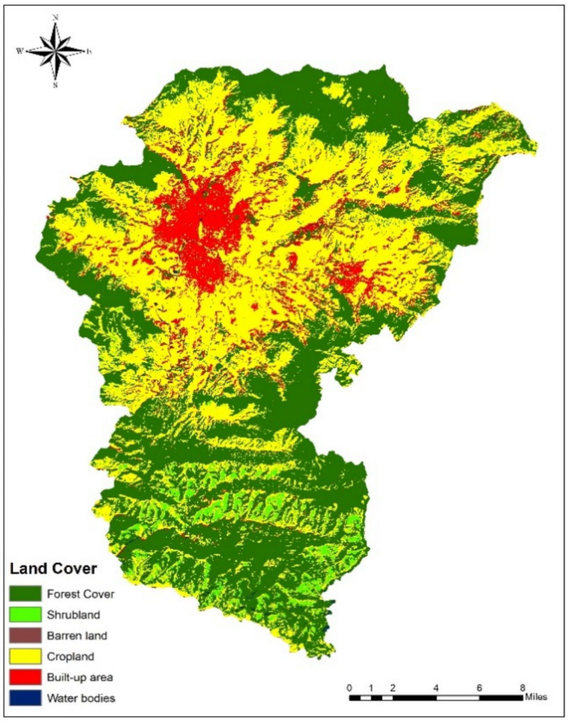
3.2. Analysis of Land Cover Change in Kathmandu Valley

In this study, Kathmandu valley was divided into six different land cover classes for 1989, 1999, 2009, and 2019. In 1989, the land cover of Kathmandu valley was dominated by forest area at 43.83% of the total area. There was less barren or unused land (0.1%) than in other land cover types. The built-up area covered 9.54% of the total area of Kathmandu valley, which is the last area of built-up during the study period. Cropland, shrubland, and waterbody were 43.67%, 2.3%, and 0.5% of the total land cover area of Kathmandu valley, respectively. In 1999, 2009, and 2019 forest cover shrunk to 43.77%, 40.97%, and 31.41% of the total land cover of Kathmandu valley, respectively. On the contrary, cropland was nearly constant at 41%, 40.97%, and 41.77% in 1999, 2009, and 2019 respectively. The built-up area is responsible for the largest transfer in the land cover by the increasing area of 2148.21 ha, 3,517.11 ha, and 10,014.39 ha in 1999, 2009, and 2019, respectively.

Comparing the land cover of 1989 and 2019, one can see significant variation in the land cover classes with a drastic reduction in the water bodies (91.56%) and cropland (4.35%). There has been a rapid growth in the rate of barren land, built-up area, and shrubland, amounting to 21.14%, 112.45%, and 173.68%, respectively. Urban (built-up) areas have increased exponentially during the study period. This has occurred at the expense of forest cover (decreased by 28.3%) and, to a lesser extent, cropland (decreased by 4.4%). Figure 3 shows the spatial distribution of the losses and gains of the classified land cover types in Kathmandu valley. These expansions are associated with the conversion of cropland into the urban settlement and the reduction in the forest cover for further expansion of cropland. Urban expansion has been accelerated in the nearby area of cities and built-ups along the main roads forming the new settlements Figures 4 and 5 illustrated the transition of land cover changes between the years 1989 and 2019 whereas the status of land cover for the different years is shown in Tables 6 and 7 shows the change in land cover between study periods.

Table 6. Landcover Status in 1989, 1999, 2009, and 2019.

LULC Class	1989		1999		2009		2019	
	ha	%	ha	%	ha	%	ha	%
Forest Cover	40,907.34	43.83	40,854.60	43.77	38,238.57	40.97	29,319.93	31.41
Shrubland	2149.38	2.30	2704.32	2.90	3160.08	3.39	5882.49	6.30
Barren land	112.41	0.12	256.68	0.27	1203.12	1.29	136.17	0.15
Cropland	40,763.97	43.67	38,271.15	41.00	38,242.17	40.97	38,990.61	41.77
Built-up Area	8905.77	9.54	11,053.98	11.84	12,422.88	13.31	18,920.16	20.32
Waterbodies	499.32	0.53	197.46	0.21	71.37	0.08	42.12	0.05
Total	93,338.19	100.00	93,338.19	100.00	93,338.19	100.00	93,338.19	100.00



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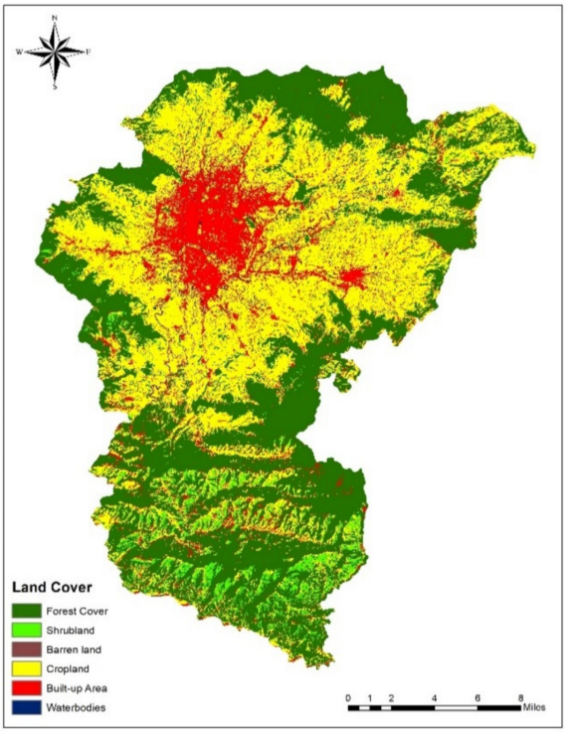

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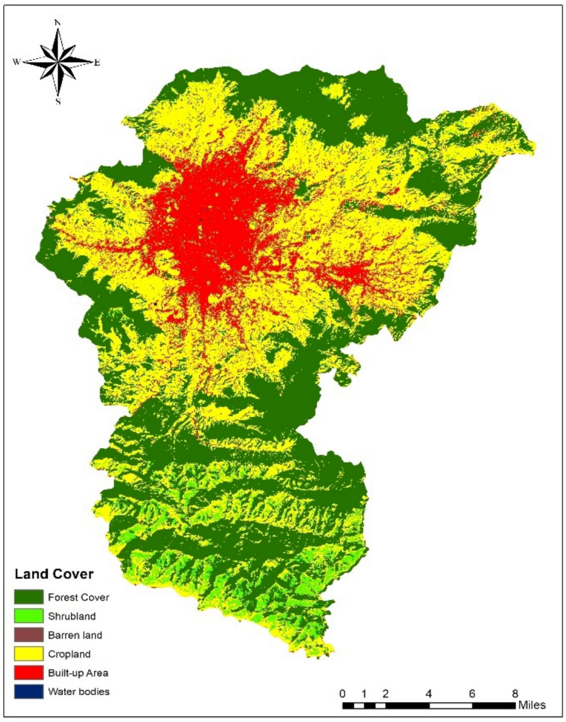

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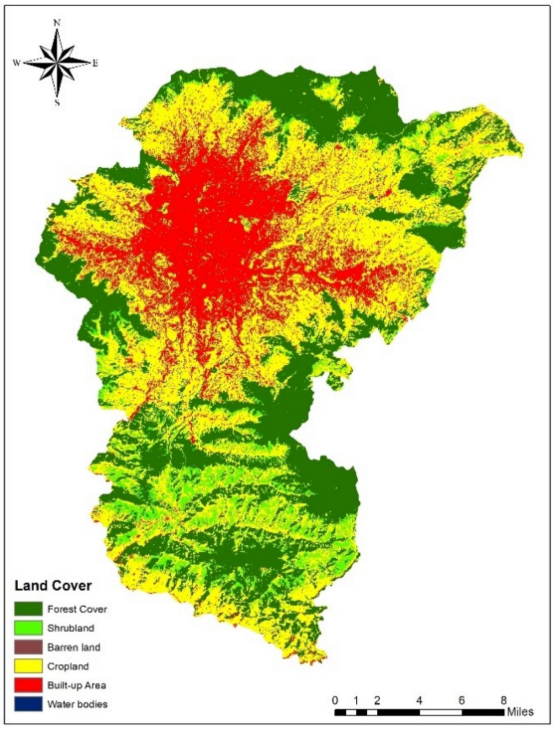

(**d**)

Figure 3. Spatial distribution of LULC in Kathmandu valley for (**a**)1989 (**b**) 1999 (**c**) 2009 (**d**) 2019.

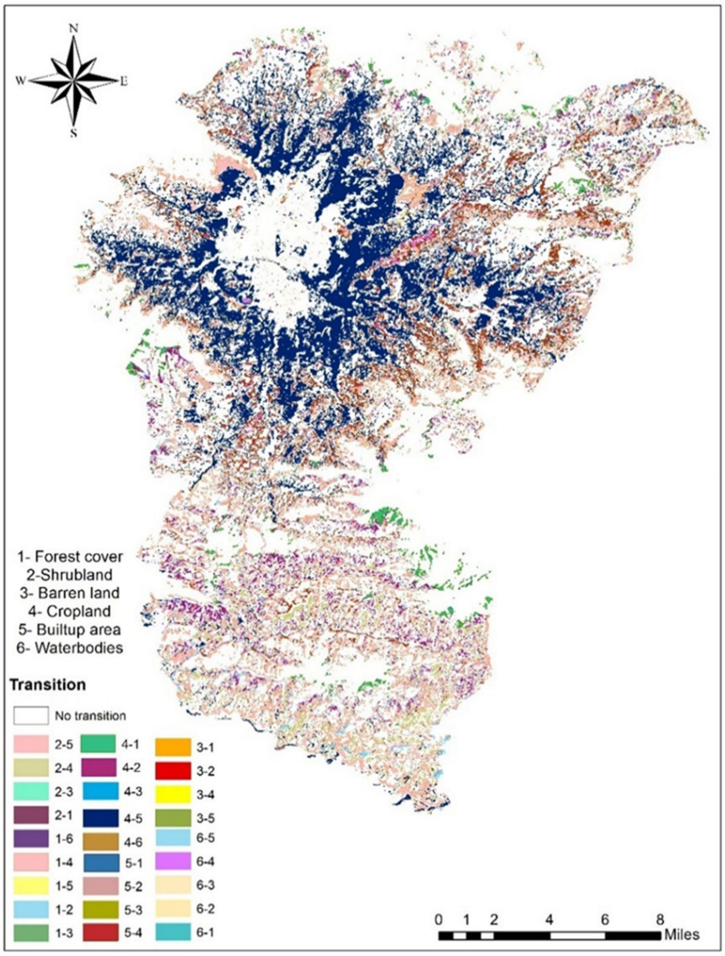

Figure 4. Distribution of the LULC class that transitioned from 1989 to 2019.

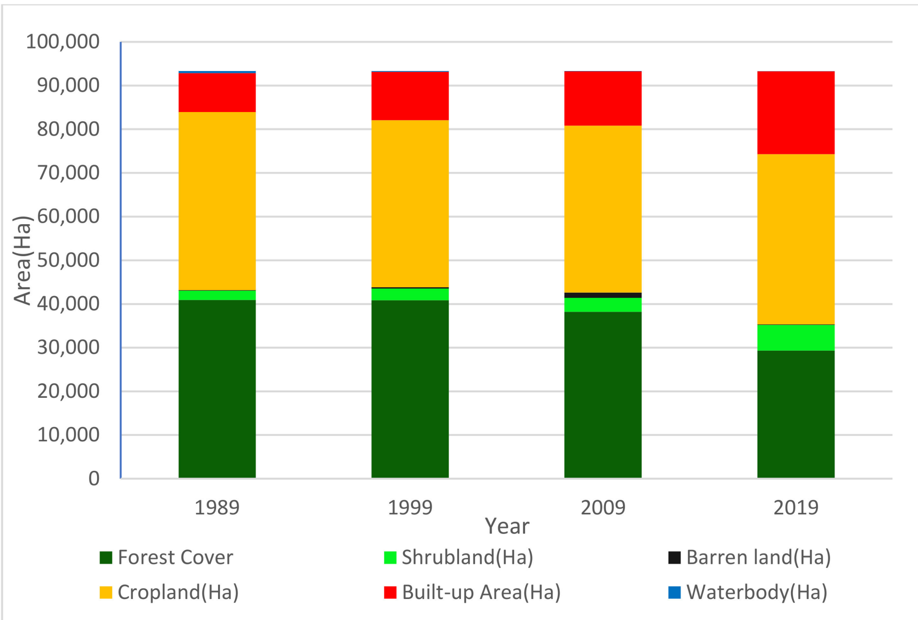

Figure 5. Comparison of land cover categories in hectares for 1989–2019.

Table 7. Change in Land Cover during the Study Period.

LULC Class	1989–1999		1999–2009		2009–2019		1989–2019	
	ha	%	ha	%	ha	%	ha	%
Forest Cover	−52.74	−0.13	−2616.03	−6.40	−8918.64	−23.32	−11587.41	−28.33
Shrubland	554.94	25.82	455.76	16.85	2722.41	86.15	3733.11	173.68
Barren land	144.27	128.34	946.44	368.72	−1066.95	−88.68	23.76	21.14
Cropland	−2492.82	−6.12	−28.98	−0.08	748.44	1.96	−1773.36	−4.35
Built-up Area	2148.21	24.12	1368.9	12.38	6497.28	52.30	10014.39	112.45
Waterbodies	−301.86	−60.45	−126.09	−63.86	−29.25	−40.98	−457.20	−91.56

3.3. Assessment of Ecosystem Service Value Changes

In this study, the ESV for the Kathmandu valley was calculated using values derived by Costanza et al. and modified by Xie et al. for the Tibetan Plateau. Based on the ESV coefficient modified by Xie et al. this study estimated the value for 1989, 1999, 2009, and 2019. Over the study period of 30 years, it was discovered that variation in the ecosystem service differs in gain and losses across space and time. It shows there is a significant decrease in the overall ecosystem service value and an increase in the built-up and barren land area, which is the major factor for the reduction in ESV. From the estimation, it was found Kathmandu valley stored USD 122.84 million value of ecosystem services in 1989, an amount that declined with each passing year. By 2019, the total ESV had fallen to USD 97.54 million. The ESV for the classified shrubland, cropland, and water bodies was USD 2.95, USD 26.76, and USD 1.29 million, respectively, for 1999. Between 1999 to 2009, the ESV decreased by 5.03%, which was near USD 4.2 million. The ESV for the categorized land was USD 82.93, USD 3.44, USD 26.74, and USD 0.467 million for forest cover, shrubland, cropland, and waterbodies, respectively. From 2009 to 2019, the ESV value dropped by USD 16 million (14.12%). Among the different LULCs, forest cover comprised higher ecosystem service values as compared to other land cover types due to larger area coverage. The forest cover was measured at USD 63.59 million per year in 2019, cropland at USD 27.27 million per year, waterbodies at USD 0.27 million per year, and shrubland at USD 6.4 million per year, respectively 2019. The dense forest cover is responsible for the ecosystem services to improve habitat quality, soil erosion, and other complements [60]. Though there is less area covered by the water bodies than shrubland, due to the higher value of the ESV coefficient, it contributes significantly higher. However, the total estimated ESV decreased by 2.63%, 7.53%, and 20.60% in 1989–1999, 1989–2009, and 1989–2019 respectively (Table 8). From 1989 to 2019, the largest decrease in the ecosystem service values is in the forest cover class, with USD 25.13 million (28.33%). During 1989–1999 and 1999–2009, there was a slight reduction in the forest cover, but there was a larger value drop during 2009–2019. The study found cropland slightly decreased during 1989-1999 and 1999–2009 but increased in 2009–2019 (Figure 6 and Table 8).

Table 8. Ecosystem Service Values for Kathmandu valley in 1989, 1999, 2009, and 2019.

LULC Class	1989	1999	2009	2019
Forest Cover ($)	88,721,475.29	88,607,090.66	82,933,340.16	63,590,236.98
Shrubland ($)	2,341,083.20	2,945,518.30	3,441,927.54	6,407,149.28
Cropland ($)	28,509,097.70	26,765,694.18	26,745,426.43	27,268,862.92
Waterbody ($)	3,272,028.98	1,293,949.46	467,685.47	276,011.10
Total ($)	122,843,685.17	119,612,252.60	113,588,379.60	97,542,260.28

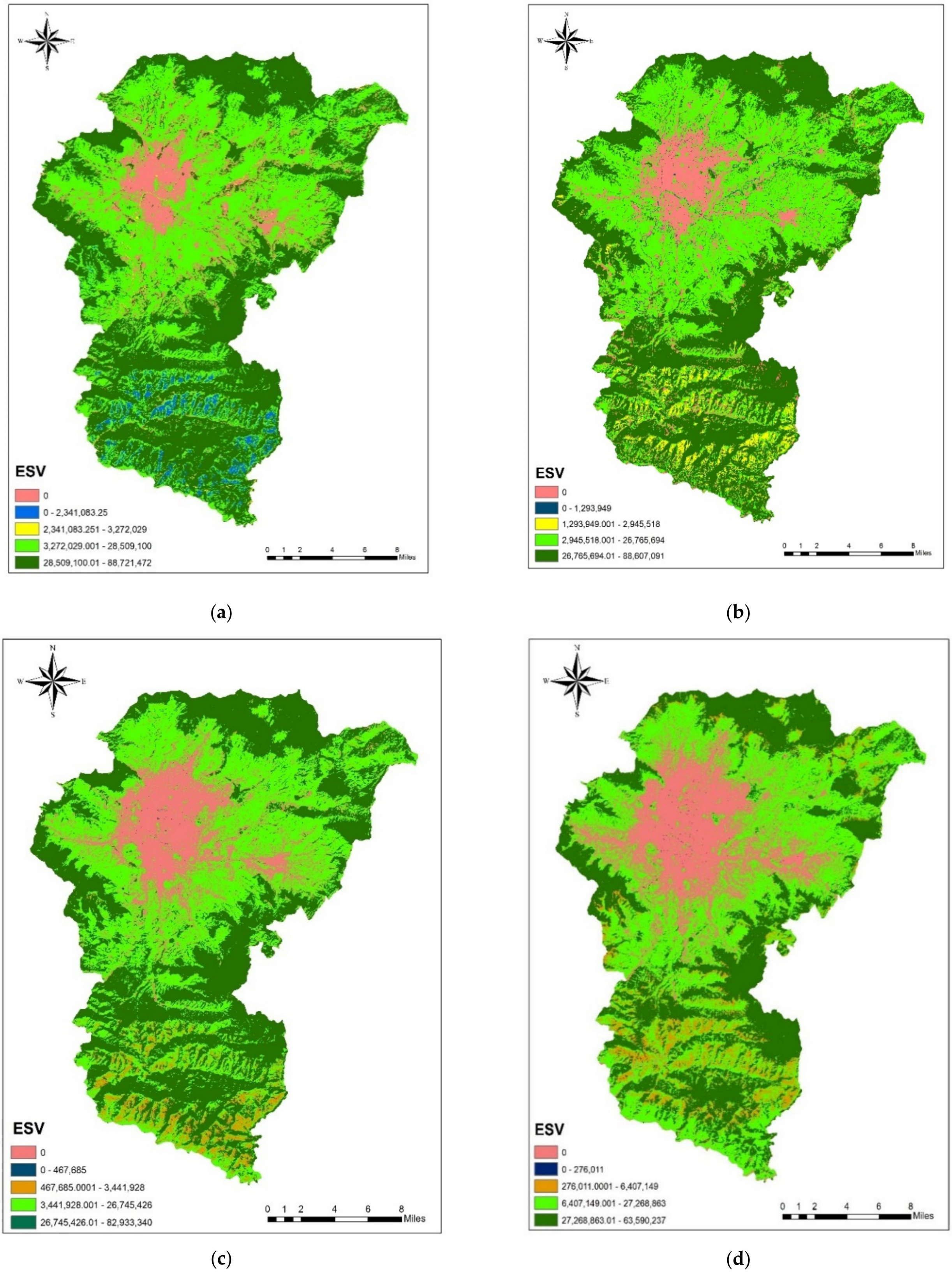

Figure 6. Spatial distribution of ESV in Kathmandu valley in (**a**) 1989 (**b**) 1999 (**c**) 2009 (**d**) 2019.

The variation in cropland is affected by urbanization and deforestation. The rapid rural-urban migration, increase in the densely built-up area, and degradation of forest cover into shrubland is the main reason for decreasing ecosystem value in forest land cover type [62]. The summary of temporal changes in ESV value for the different land cover of the study area is presented in Table 9. According to the result of the study, there is no doubt that the conversion of the forest cover into other land cover reduces the total ESV of Kathmandu valley (Figure 7 and Table 9).

Table 9. Change in ESV during the study period in USD and percentage.

LULC Class	1989–1999		1999–2009		2009–2019		1989–2019	
	$	%	$	%	$	%	$	%
Forest Cover	−114,384.62	−0.13	−5,673,750.51	−6.40	−19,343,103.18	−23.32	−25,131,238.30	−28.33
Shrubland	604,435.10	25.82	496,409.23	16.85	2,965,221.75	86.15	4,066,066.08	173.68
Cropland	−1,743,403.52	−6.12	−20,267.74	−0.08	523,436.48	1.96	−1,240,234.78	−4.35
Waterbody	−1,978,079.52	−60.45	−826,263.99	−63.86	−191,674.37	−40.98	−2,996,017.88	−91.56
Total	−3,231,142.57	−2.63	−6,023,873.00	−5.03	16,046,119.32	−14.12	−25,301,424.89	−20.60

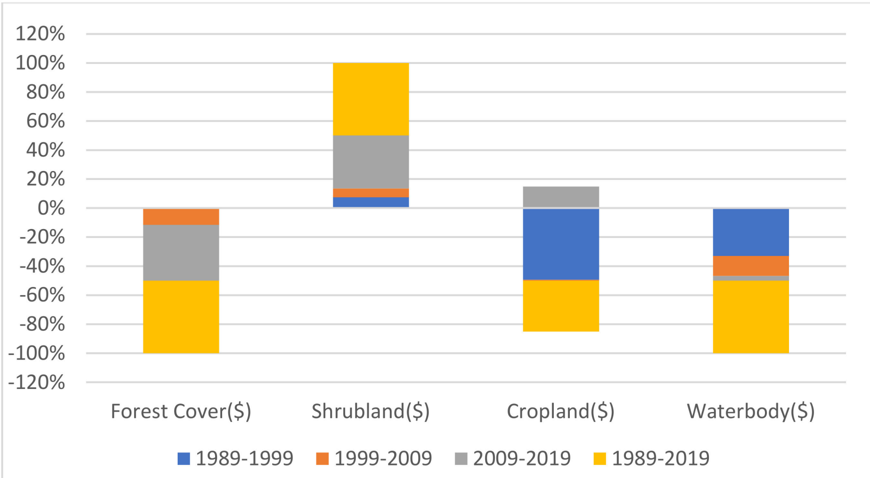

Figure 7. Proportions of ESV for different land types during study periods.

4. Discussion

Compared to other estimation methods, LULC analysis is a widely used method for measuring the spatial and temporal variation of the ecosystem service values at a regional and global scale. Kathmandu valley is one of the most rapidly urbanizing cities in South Asia, which has been experiencing rapid land cover changes for the last 30 years. In this study, the ecosystem services values of Kathmandu valley were measured using remote sensing and geographical information. As per the quantitative evidence of this study, Kathmandu valley has witnessed considerable land cover changes since 1989. Previous studies have also found that the Kathmandu valley was dominated by the rapid change in urbanization, deforestation, and variation in the agricultural land area between 1989 to 2019 [59,63,64]. Wang et al. studies on LULC of Kathmandu district found the built-up area is increased by 52.33% [63], which justifies the surges of population density in Kathmandu rather than in Lalitpur and Bhaktapur districts. The rate of change in land cover in Kathmandu valley was found to be higher than in other parts of the country [54,56,63,65]. A study of LULC on a major built-up area of Kathmandu valley provides a detailed expansion of human settlement, increasing by 4.96 % and cropland reduced by 6.51% between the years 2010 to 2018, excluding suburban areas [66]. These changes were more noticeable latter part of the study period (2009-2019). The growth of the built-up area was at the expense of forest cover and, to a lesser extent, cropland.

The result shows built-up areas expanded into nearby cropland, dense forest areas changed into agricultural land, and waterbodies converted into barren land. Some parts of the remaining forest cover are converted into shrubland, degrading its quality and reducing the area for carbon sequestration, similar to the result found by Khanal et al. [64].

The increase in the dense urban settlement can be related to the growing urban area of Kathmandu valley, spreading the settlement outward as well as becoming denser due to conversion from other land covers into built-up land. During the study period, the Kathmandu valley experienced a significant loss of forest cover, with around 11,600 ha converted for the urban (built-up) purpose. Farmers also were driven by the rapid growth of the built-up area to remove the forest and increase agricultural land on the slopes. The cropland area has migrated to the outer area of urban settlement, delineated by the forest covers and shrubland. However, the rapid expansion of built-up regions over the study period may be an increase by rural-urban migration, political unrest, economic centrality, and a boom in real estate business in the Kathmandu valley, as found by Ishtiaque et al. [67] and Khanal et al. [64] which demands sustainable management of urban areas including nature-based solution pathways. Rural-to-urban migration accounts for the majority of this expansion, which is fueled by the economic opportunities accessible in the capital city compared to rural areas [20]. Throughout the 1990s, urban in-migration accounted for up to 40% of population growth [67], and as per the CBS report in the 2000s, the net inflow of rural-urban migrants was 36% [68]. Land abandonment in the hills and conversion of agricultural lands to urban areas could have resulted from the loss of highly fertile agricultural lands and, as a result, a reduction in food production [69]. This might be an issue for a food-security-sensitive country such as Nepal. Barren land was increased slightly in 1999–2009 and then decreased dramatically in 2009-2019 which is a quite common pattern for the conversion of other land types to urban settlements. Government and policy changes in managing land and land-related resources may be responsible for the differences in land cover between the years [70]. Public policies are significant drivers of LULC transformation and play an equal role in encouraging long-term land use [71]. Government policies on land use and management continue to be technical, with little regard for the role of land users, their experiences, knowledge, and adaptability.

The loss of ecosystem services as a result of urbanization is not only a national or regional problem but a worldwide one [72–74]. This study estimated the total annual ecosystem service values in Kathmandu valley decreased from USD 122.84 to USD 97.54 million between 1989 and 2019. It was found that ESV dropped by 7.53% between 1989 to 2009 whereas Shrestha & Acharya also found a similar rate of reduction in ESV value in Kathmandu valley [73]. Similarly, the capital city of the neighboring country India observed dropped in ESV by USD 56 ha^{-1} $year^{-1}$ [74]. These changes will affect ecosystem architecture, functions, species geographic distributions, and ecological resilience, all affecting urban ecosystem services [73]. Changes in LULC are likely to have similar effects in cities around the world, such as increasing urban heat island effects, flood security hazards, air quality degradation, and difficulty caused by different species [75]. The decline in the forest area cover in the Kathmandu valley has a significant impact on the forest ecosystem services. Due to forest land degradation, the economic loss associated with the dense forest was estimated at USD 25.13 million per year (−28.33%). Ecosystem services are harmed by haphazard urbanization and the loss of forest and agricultural land [32,76].

Global studies conducted around the world found that the significant causes of loss of ecosystem services in urban areas are severe consequences of overpopulation [77–79]. Over a thirty-year study period, the Kathmandu valley has experienced major changes in the land cover, which caused the loss of 20.60% of ecosystem service value. From the conversion pattern, it was found that the extension of the urban areas into cropland increases the deforestation rate for expanding agricultural land, reducing the share of forest cover in ecosystem service value. The healthy ecosystem of Kathmandu valley was found to be altered during the study period by providing goods and services through human activities. This study found the water bodies of the study area had dropped from USD 3.27 million in 1989 to USD 0.27 million in 2019. The riverside became a trash dump due to uncontrolled urbanization and rapid urban growth [80]. When comparing the result of LULC for this study with other studies conducted in the different river basins of Nepal, the Koshi River basin was the most stringent [62], followed by the Gandaki River basin, with the least change in Karnali River basin [32]. Sharma et al. concluded that ESV is decreasing trend in the Terai Arc Landscape in lowland Nepal [26]. One of the significant observations of the LULC effect on the ESV of Kathmandu valley is also an increase in the land surface temperature creating an urban heat island. Recreational ecosystem services, such as those supplied by urban nature, are a significant aspect of a high-quality living environment and are beneficial to public health [76]. Urban vegetation has the potential to help with carbon sequestration and, consequently, climate change mitigation. The findings of this research can be used as a theoretical foundation for environmental policy formation in Kathmandu valley and implementation based on the studied area's features. The government of Nepal has adopted to follow the environmental protection act 2019 [81] and the National Climate Change Policy 2019 [82]. This action envisions future ecological priority and green development resulting in a clean and livable environment. In Kathmandu valley, this requires water resource regulation, water quality assurance, and environmental protection [83]. Ecological security programs in the study area could be used to accomplish the dual effect of environmental protection and poverty reduction as applied in Xiang city of China [84,85]. Climate change and biological diversity are the most serious risks to ecosystem services protection. Land use planning is a solution for integrating urban community structures in cities and urban regions to reduce CO_2 emissions, air pollution [86], and solid waste management [87]. The difficulty is to build well-managed settlements preserving environments and critical ecosystem services including recreational services, stormwater absorption, and carbon sinks [88]. Effective planning can mitigate the adverse effects of urban growth and increase ecological services.

Though this methodology is easy to adopt and cost-effective, there are a few limitations. Firstly, there may be uncertainty due to the quality of satellite images. The image selection from a suitable season is significant. In this study, Landsat image was acquired only post-monsoon season with minimum cloud cover to increase the accuracy between the databases. Utilizing high-resolution satellite data can improve classification outcomes and ESV estimation over a large area. Secondly, the ESV coefficient can affect the precision of input data. This study uses the local scale value coefficient derived by Xie. et al. [34] in the Tibetan plateau, which provides the actual value of ecosystem services.

5. Conclusions

This study investigated the trend of the LULC and variation of ESV in Kathmandu valley using remote sensing data for thirty years, from 1989 to 2019. According to the above analysis, the total value of ecosystem services was USD 97.54 million per year in 2019, where the most valuable land cover type was found to be forest area covers, having USD 63.59 million per year ecosystem service value. As for individual land cover types, all land cover varied from 1989 to 2019 and affected the total ecosystem service value of Kathmandu valley. The land cover transitions show that built-up areas and water bodies account for most of the loss in ESV. The increase in the ESV only occurs in the shrubland land-use class, and the degradation of dense forest cover in shrubland is the main reason for the increment in ESV in the shrubland land class. LULC change is being driven by a combination of factors, including growing urban populations and their livelihoods, unplanned urban settlement, transportation congestion, air pollution, unmanaged solid waste disposal, and global climate change. The global price structure would be substantially different if ecosystem services were truly compensated for in terms of their valuable contribution to the global economy. The cost of goods that rely on ecosystem services, whether directly or indirectly, would be significantly higher. If the value of ecosystem services were properly accounted for world's gross national product would be considerably different in terms of both volume and composition. However, the findings of this study suggest that the current value of ecosystem services is, at best, a static snapshot of a biosphere that is a complex and dynamic system. Nevertheless, this study has provided new insight into variation in ESV in the region over the past 30 years of the study period. The results can be used by policymakers for urban planning, conservation of natural ecosystems, climate change mitigation and adaptation plans, and maintenance of biodiversity conservation. This study recommends integrating nature-based solutions in urban development plans, policies, and financial support for implementing smart interventions. The findings also suggest that policymakers should take into account the regional heterogeneity of ES supply and the gradient analysis for a more accurate definition of ES supply. An effective decision and plan can be prepared to deal with the growth of urban settlements, the depletion of forest cover, the reduction in open space, the variation of farm spaces, and the reduction in small to medium size water bodies. Some recommended plans are green roof space, rainwater harvesting, sufficient use of clean and green energy, and plantation in available spaces at large scales with the active participation of communities and coordination with governmental bodies to enhance the ecosystem services by increasing LULC dynamics. This study clearly states the importance of remote sensing and satellite images in quantifying land cover changes and ecosystem conservation. The result of the study is useful in land use, and land cover model analysis tests alternate approaches for determining how they affect the ecosystem. ESV calculation is a conclusive and suitable method for valuing the ecosystem in terms of money, giving the scientific foundation for directing the policies. It can be used to compare the accuracy and classification of the land using various techniques and models. The most critically affected ecosystem service function in Kathmandu valley provides a case study for research. Additionally, by creating future scenarios that take into account the urbanization pattern and demographic expansion in the landscape and evaluate their effects on ESV, the findings could be expanded. Since this study compared data from several other ecosystems, the information it contains will be crucial for Nepal's future research and policy development.

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Life cycle assessment of municipal solid waste management in Kathmandu city, Nepal – An impact of an incomplete data set

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ABSTRACT

Few studies have been done about engineered facilities related to waste collection, treatment, and disposal in the waste management sectors across Nepal. The decision support system is not well established, resulting in poor planning and execution of waste management. Available data for performing a life cycle assessment (LCA) is limited. We used an LCA model to investigate waste management options for Nepal's capital, Kathmandu. We also tested the hypothesis that exclusion from the LCA model of variables for which there was no data would make no difference in the management rankings. The assessment was based on three scenarios: business as usual, including collection, transportation, and landfilling; recycling; and conjunctive disposal comprised of composting and landfilling. The LCA methodology we used includes detailed unit processes and quantified values of various resources and emissions to compute the impact level on the environment. The contribution of the collection, transportation, landfilling, and recycling was calculated as global warming potential, acidification potential, eutrophication potential, and fuel energy consumption for each scenario. Scenario 3 ranked higher than scenarios 1 and 2 based on available data. The results were based on the environmental burden of metric tons of municipal solid waste handled at landfills, regardless of what was recycled and composted. Scenario 3 yielded minimum environmental impacts and was a cost-efficient option. Using a range of literature values for the missing variables, it was shown that the excluded variables made no difference in the scenario rankings. The study successfully employed the LCA as a decision-making tool in waste management in Kathmandu, which can be useful for other cities in developing countries.

Author statement

Mohan B. Dangi: Visualization, Methodology, Data curation, Interpretation of results, Writing- Original draft preparation, Reviewing, Editing.

Om B. Malla: Conceptualization, Investigation, Writing- Original draft preparation, Software.

Ronald R.H. Cohen: Writing- Reviewing, Editing, Calculation, Validation, Software.

Nawa R. Khatiwada: Supervision.

Samir Budhathoki: Calculation, Writing- Reviewing, Editing.

1. Introduction

Waste has been an inevitable byproduct of human civilization, mostly arising from social and economic aspects of people's lives (Gautam, 2011). Based on the rate and quantity of waste generation, its types, and composition, alternative methods could be selected to manage waste streams. Environmental assessment tools like life cycle assessment (LCA) can and have been employed to integrate data on the characteristics of the waste, the environmental impacts of the various wastes, and the advantages and disadvantages of waste management protocols (Khorasani et al., 2012; SETAC, 2020). LCA has proven to be useful to evaluate the performance of municipal solid waste (MSW)

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management (Assamoi & Lawryshyn, 2011). The LCA "cradle to grave" approach could be effective in choosing the proper tool to help solve the MSW problem we observe in Nepal (Barton et al., 1996; Khorasani et al., 2012). LCA includes not only a product within the system, but also services, processes, or activities (Bahor et al., 2010).

Also, life cycle inventory (LCI) is one component of an LCA. The entire suite of material and energy resources can be used as inputs and the products and emissions that are the outputs need to be recognized and computed in the LCI (Abeliotis, 2011). Ibanez-Fores et al. (2021) used LCA, LCI, and life cycle impact assessment (LCIA) tools to achieve waste recovery goals in the medium- and long-term in a Brazilian city. LCIA permits the characterization and mitigation of various problematic substances. For example, after the emissions from an uncontrolled disposal facility have been quantified, it is important to calculate in what way those environmental emissions will affect the surrounding. JRC (2011) comprehensively provided a compilation of the key impacts coming from open dumps, emission to every impact category, and appropriate indicators to come up with the associated impacts. Ferrari et al. (2021) also took a similar approach to utilize LCA and LCI along with enterprise resource planning in an industry environment. Other studies that used LCA for waste handling, to recommend the effective method for sustainable solid waste management (SWM) and energy recapture include Arena et al. (2015), Dong et al. (2018b), and Jensen et al. (2016). Arena et al. (2015) found that, in treating residual MSW in Europe, incineration has less environmental burden than gasification among the impact categories. Likewise, using the LCA, Dong et al. (2018a) established that incineration plants have a lower environmental impact than pyrolysis and gasification. Several recent studies (Dastjerdi et al., 2021; Ferrari et al., 2021; Ghasemi-Mobtaker et al., 2020; Ibanez-Fores et al., 2021; Khanali et al., 2021; Levis et al., 2017; Mostashari-Rad et al., 2021; Nabavi-Pelesaraei et al., 2020, 2021) have also used LCA, LCI, and LCIA tools to successfully manage MSW.

Wang et al. (2020) stated that LCA was effective in addressing important issues such as greenhouse gas (GHG), more accurately known as radiatively active gas, emissions from MSW operations because of enhanced waste collection, treatment, recycling, and the prevention of waste. Dastjerdi et al. (2021) and Evangelisti et al. (2015) stressed that LCA is an upcoming instrument to assess the environmental impacts of a waste treatment operation. LCA can be helpful in decision-making concerning acidification, global warming, environmental toxicity, and human impacts at various phases of waste management (Dastjerdi et al., 2021; Ripa et al., 2017; Tunesi, 2011). Other contemporary uses of the LCA tool include evaluating environmental harm due to irrigation systems during barley production in Iran (Ghasemi-Mobtaker et al., 2020), analysis of environmental impacts associated with horticultural inputs (Mostashari-Rad et al., 2021), examination of multi-objective energy optimization and emission generation in walnut production in Iran (Khanali et al., 2021), assessment of the likelihood of using solar technologies in the production of sunflower in Iran (Nabavi-Pelesaraei et al., 2021), and investigation of eco-efficiency variations in paddy production in Iran (Saber et al., 2021).

In the present context, while the studies of life-cycle environmental emissions from sanitary landfills are increasing, there have been few studies covering the uncontrolled disposal of waste (Levis et al., 2017). Here are a few such studies: GHG emissions from landfill sites by Banar et al. (2009) for Eskisehir, Turkey; Batool and Chuadhry (2009) for Lahore, Pakistan; Manfredi and Christensen (2009) for Denmark; Thanh and Matsui (2013) for Da Nang, Vietnam; Oyoo et al. (2014) for Kampala City, Uganda; and by Guan et al. (2015) for Zhejiang Province, China.

There has been limited research and a lack of public knowledge about the long-term impact of uncontrolled dumping in Nepal and other locations (Dangi, 2009; Dangi et al., 2006, 2017; Levis et al., 2017). In this paper, we used LCA procedures to understand the impact of uncontrolled dumping of MSW and the effectiveness of a variety of SWM approaches in Kathmandu city, also known as Kathmandu, the capital of Nepal. (See the basic information about the study area along with Fig. S1 under Supporting Information of the manuscript.)

We assess the life cycle of MSW management in Kathmandu. We then compared the results with alternative management methods and relate our findings to recent studies (Iqbal et al., 2020; Khandelwal, Dhar, et al., 2019; Khandelwal, Thalla, et al., 2019; McDougall et al., 2001, 2008; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Nabavi-Pelesaraei et al., 2020; Silva et al., 2021; Taşkın & Demir, 2020). Our paper first examines the current waste management practices in Kathmandu in detail and then evaluates the environmental impact scenarios, including metrics on global warming, acidification, eutrophication, and energy consumption related to SWM. The focus of this study is to characterize the environmental impacts of existing SWM in Kathmandu city and compare the results to those from three scenarios of SWM described in subsection 2.1. The three scenarios that we developed are SWM systems that include various MSW processing and/or disposal methods. The scenarios were developed and then compared based on their environmental impacts, i.e., global warming potential (GWP); acidification potential (AP); eutrophication potential (EP); and total fuel energy consumption (FEC) for collection; transportation; and management of MSW from the point of waste generation to landfilling.

The goal is to apply LCA to select solutions to the long-term problems of MSW disposal, thereby addressing health issues; water and air pollution; and coming up with environmentally sound waste disposal in Nepal.

Generally, compositing is considered one of the major techniques to manage organic waste (Fadhullah et al., 2022) and it can serve as an alternative to landfill for recycling organic waste as it is cost-effective and less complicated (Ajaweed et al., 2022). Organic solid waste normally consists of higher organic carbon content, which can release carbon resulting in greater GHG emissions into the atmosphere (Bian, Zhang et al., 2022). An appropriate method of managing organic solid waste needs to be adopted to prevent carbon loss, mitigate GHG emissions, and maintain carbon neutrality (Mulya et al., 2022).

A technique with a lower carbon footprint can be an effective approach for organic SWM to control GHG emissions (Huang et al., 2021). Several methods, i.e., landfilling, anaerobic digestion, composting, incineration, thermal conversion, etc., have been widely used to manage organic solid waste (Huang et al., 2022; Ye et al., 2023). However, composting along with an aerobic and anaerobic reaction occurring within the soil can convert the biodegradable organic waste in soil fertilizers to stable compost formation (Ajaweed et al., 2022). A study suggested that composting not only accounts for plant productivity and soil quality, but it also leads to higher crop yields reducing waste volume and eliminating pathogens and weeds (Vlachokostas et al., 2021). Conversion of organic portion of MSW into an earthy, humus like substance by the action of bacteria and microbes can be broadly categorized into two different phases, degradation and humification (Wei et al., 2022). Carbon losses occur during degradation; however, humification can sequester carbon in the soil (Huang et al., 2022). Composting for the most part is another method to manage organic sold waste preventing GHG emissions to meet the global carbon balance.

It is important to note that the data set, the only one available at the time, did not include historical data concerning the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation. Therefore, one of the goals of this study was to find out if the incomplete data had any significant impact on the modeling results and decision-making. Examination of the literature suggested that these missing variables would likely have no impact on the ranking of the scenarios in our study. Thus, we were determined to discover whether this was the case in Kathmandu, Nepal. The ultimate contribution of the study is to provide effective, economically sound, and data driven decision-making tools for SWM in low-income countries.

Our study is divided into seven parts: introduction (current section), materials and methods, results and discussion, environmental impacts, policy implications, conclusions, and recommendations.

2. Materials and methods

The European Union regulations on applying LCA require a hierarchical system based on four levels: reduction of solid waste generation, recovery of material, recovery of energy, and landfill disposal (Feo & Malvano, 2008). The phases of LCA procedures include goal and scope definition, LCI, LCIA, and interpretation (Clift et al., 2000). The goal and scope definition describes the purpose and extent of a study to identify the intended audience and to describe the problem that will be addressed. Then there will be a comparison of alternative solutions. While the LCI focuses on a qualitative analysis of mass and energy fluxes, the LCIA is directed to evaluate the magnitude and significance of potential environmental impacts. Then there is an interpretation of the results from the previous phases. This interpretation connects the goal and scope definition with other findings to reach conclusions and recommendations for the system of study (Assamoi & Lawryshyn, 2011). To complete the study, we used three scenarios to compare the alternatives for MSW management in Kathmandu city by employing the specifications of the International Organization for Standardization (ISO) series 14,040 about LCA (ISO, 2006). The three scenarios consist of business as usual (BAU), including collection, transportation, and landfilling; recycling; and conjunctive disposal procedure comprised of composting and landfilling. These scenarios are included in Fig. 1. Similar approaches were also utilized by other researchers (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Nabavi-Pelesaraei et al., 2020; McDougall et al., 2008). This paper describes the LCA of SWM in Kathmandu, which was developed into four phases. These phases were described by McDougall et al. (2001 and 2008) and Nabavi-Pelesaraei et al. (2020).

The three scenarios included in this study with system boundaries are described here.

2.1. Scenarios

2.1.1. Scenario 1—Business as usual, including collection, transportation, and landfilling

It consists of three steps: collection, transportation, and landfilling of MSW. This illustrates the current status of MSW management undertaken by Kathmandu. About 10% of total waste is recycled in Kathmandu (Bhattarai, 2003; Dangi et al., 2009). Since plastics, paper, and glass make up 11%, 9%, and 5% of the total waste, respectively, another 15% of the recyclable material is still being landfilled in Kathmandu (Waste composition of the study is mentioned in subsection 3.2 later.). Given the actual recycled amount was so little, recycling was not considered in Scenario 1.

2.1.2. Scenario 2— Recycling

It assumes a system where recyclable waste, primarily paper, plastics, and glass, i.e., 25% of the total MSW, is recovered and recycled while the remaining waste is transported to the landfill. Scenario 2 is assessed to find the possibility of improving the existing SWM in Kathmandu.

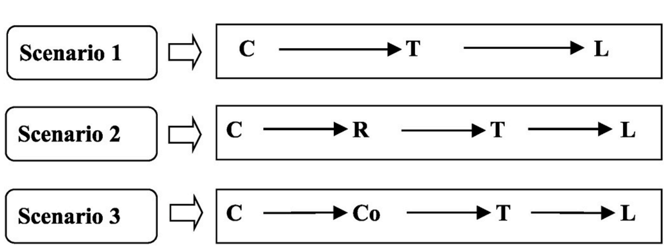

Fig. 1. Scenarios considered in the study (C = collection, T = transportation, L = landfilling, R = recycling, and Co = composting).

2.1.3. Scenario 3— Conjunctive disposal comprised of composting and landfilling

Conjunctive disposal systems consist of composting and landfilling that employ aerobic as well as anaerobic digestion of 63% of the organic waste before landfilling. Therefore, it only assumes that the remaining 37% would end up in the landfill. These are common practices of MSW treatment methods in Europe (Ozeler et al., 2006).

2.2. Data collection

The fact sheet including day-to-day waste generation and operation and management statistics for MSW in Kathmandu was collected from the Solid Waste Management Section of the Environment Management Department of the city. The data includes the total waste collected by Kathmandu city in 2011. The breakdown of the data consists of the population, waste stream characteristics, collection rate, composition by weight, and operational conditions of landfills. The percentage of landfill input, waste processing capacity, composting rate, recycling rate, fuel energy consumption cost in Nepali Rupee (NR) per metric ton (mt), and distance to the landfill site in kilometers are used in this inventory. (A US dollar was equivalent to NR 87.64 at the time of the study.) Also, the city provided a monthly log of fuel energy consumption used in SWM activities. The FEC included: the types of fuel used, and the total amount of money expended on the fuel. Secondary data were collected through a detailed literature survey and review using multiple online databases and applicable research papers on LCA of SWM from South Asia as well as other developing countries.

2.3. LCA framework

2.3.1. Goal and scope definition

As described toward the end of section 1 above, the goal of the study was to characterize the environmental impacts of existing MSW management in Kathmandu city and compare the results to those from three alternate scenarios of MSW management. The three scenarios that we developed are SWM systems that include various MSW processing and/or disposal methods. The scenarios were developed and then compared based on their environmental impacts, i.e., GWP, AP, EP, and total FEC for collection, transportation, and management of MSW from the point of waste generation to landfilling.

To characterize waste generation and environmental impacts, it is necessary to define a functional unit as the total waste generated in a given geographical region for a period, i.e., expressed in kg or mt per year (McDougall et al., 2001; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). In this study, the functional unit is expressed as the total amount of waste generated in Kathmandu in a year: 168,265 mt as per the total collection of solid waste. This is generated by households, commercial establishments, industries, and nearby villages and collected on road surfaces.

Another requirement for LCA studies is system boundaries. In the case of a cradle-to-grave approach inherent to the LCA procedures, the cradle is known as the moment when material loses its value from an owner's perspective, and the grave is recognized when the waste is landfilled and becomes inert as emission to air or water (McDougall et al., 2001). The direct emissions resulting from landdfilling of MSW are included in this study.

There were some limitations to the study due to a lack of historical data concerning the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation. Budgetary limitations precluded our ability to collect the data ourselves. We hypothesized that the omission of this data would have no significant impact on the ranking of the scenarios or selection of the most efficacious management tools. The emissions by energy consumption during the collection, transportation, and landfilling of MSW and transportation of fuel itself is a small part of the total emissions from the system (Eriksson et al., 2005). Also omitted from the study are the impacts of waste in the working environment, casualties during waste handling, and the impact of the odor.

We tested the hypothesis that the missing data for direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation would have minimal impact on the ranking of the scenarios. This was tested by obtaining quantitative values of these variables from the literature and establishing a range of values for the variables. The LCA model was run in multiple modes.

a) Without the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
b) With high literature values both of indirect and direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
c) With high literature values of indirect and low values of direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
d) With low literature values of indirect and high values of direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
e) With low literature values of indirect and low values of direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.

2.3.2. *Life cycle inventory*

LCI includes the collection of data for all mass and energy inputs and outputs, followed by calculation to complete the stage (McDougall et al., 2008). The net result from the LCI is the quantification of all environmental interventions including input and outputs (Coventry et al., 2016; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). These inputs and outputs consist of "energy and material balances, atmospheric emissions, waterborne emissions, solid waste, and other releases for the entire life cycle of a product, process or activity (SAIC, 2006, p. 19)." The justifications for omitting some inputs and outputs are explained in subsection 2.3.1 above.

The data under discussion in this paper also refers to the data collected and reported in subsection 2.2 above. However, the fuel energy consumption cost does not account for the fuel used by private organizations, non-governmental organizations, and community-based organizations engaged in SWM for the collection, transportation, and management of MSW.

Similarly, LCI was used as an important step to determine the flow of mass and energy inputs and outputs in MSW management by Goulart Coelho & Lange (2018) where they conducted characterization and generation of MSW. Other studies also provide emission information about the resource consumption and pollutants to produce electricity from each energy source (Flury & Frischknecht, 2012; McDougall et al., 2001; Pehnt, 2006).

The remaining information on MSW management such as recycling, composting, energy recovery, and landfilling were taken from relevant literature (Alam et al., 2008; Bhattarai, 2003; Chen et al., 2016; Dangi, 2009; Dangi et al., 2009, 2011, and 2017; Energypedia, 2020; Iqbal et al., 2014; Karki, 2015; Kuo & Dow, 2017; LaRiviere, 2007; Larsson & Sahlen, 2009; Larsson et al., 2010; MOUD, 2015; Parajuly et al., 2018; Pokhrel & Viraraghavan, 2005; Shrestha et al., 2014; Trindade et al., 2018; Wichmann et al., 2006). The potential heat content (HC) was determined using the heat value of MSW components as shown in Eq. (1) (USEPA, 2006).

$$HC = f_i \times HV_i \quad (1)$$

where,

HC is heat content, f_i is the fraction of component i, and HV_i is the heating value of component i.

The calculated heat content in (one) Million British Thermal Units per hour or MBTU was converted to megawatts of electricity using the conversion factor of a 1-MW hour of electricity is equivalent to 3.4 MBTU (USEIA, 2020). The average household demand for electricity for lighting in Nepal of 2 kW h (Energypedia, 2020) was used to calculate the number of households receiving electricity by 1 MW h.

2.3.3. *Life cycle impact assessment*

In this life cycle impact assessment, the results of the life cycle inventory are converted into a format applicable to management needs (Khorasani et al., 2012). There are internationally documented protocols and standardization for the performance of an LCIA (Hofstetter et al., 2000). To perform LCIA, a unique system and standardization that have global acceptance are not presented because currently, historical MSW management data does not exist (Hofstetter et al., 2000). As a result, the scientific methods for long-term assessment are not presented. The approach of "lower is better," used since the 1990s, is also considered in this section of the study (Khorasani et al., 2012). This approach assumes that all values from one type of stress or cumulative environmental burdens are gathered without considering the place and time of stress or whether the levels of stress are more or less than the threshold values. Also, due to innate characteristics of various stress types, they may cause detrimental changes to the environment (White et al., 1997). Therefore, the LCIA is done according to the ISO (2006) standard through the concept of indicators as outlined in Fig. 2.

The three environmental impact categories, i.e., GWP, AP, and EP were chosen and included in this study. The GWP was calculated using the Intergovernmental Panel on Climate Change (IPCC, 2021) waste model that estimates the amount of CH_4 generated from MSW and converted using the factor of 21 to CO_2 equivalent multiplied by total waste landfilled in each scenario as shown in Eq. (2).

$$GWP = [MCF(x) * DOC(x) * DOCF \times F * 16/12]\ Gg\ CH_4\ Gg\ waste^{-1} \quad (2)$$

where,

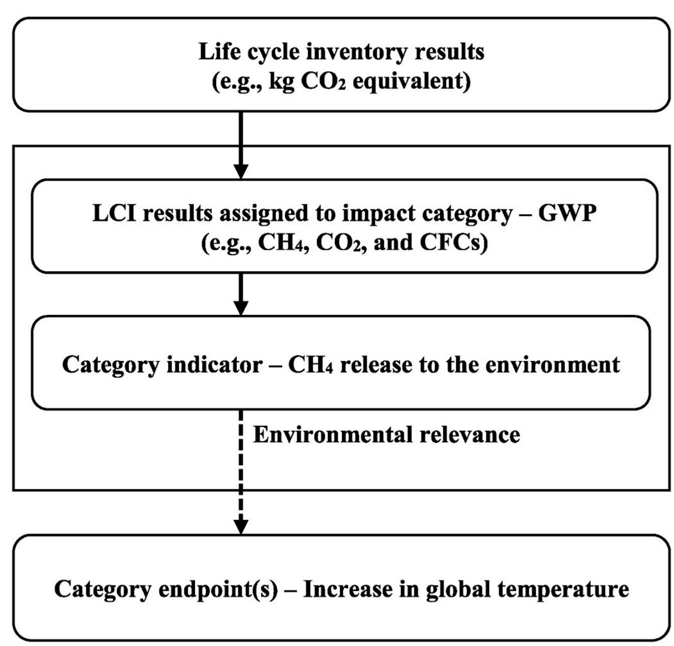

Fig. 2. Concept of indicators for life cycle impact assessment (McDougall et al., 2001).

GWP = Global warming potential,
MCF(x) = Methane correction factor in year x (fraction),
DOC(x) = Degradable organic carbon in year x,
DOCF = Fraction of DOC dissimilated,
F = Fraction by volume of methane in gas generated from landfill, and
16/12 = Conversion from C to CH_4.

The IPCC (2021) waste model, which accounts for CH_4 emissions from open dumping, is significant for the first 40 years after waste disposal and was used to calculate GWP.

Acidification potential was calculated as the product of the Nielsen and Hauschild (1998) landfill model referring to the H_2S emitted from one mt of waste and converted to SO_2 equivalent and total waste landfilled in each scenario. Eutrophication potential was reported in NO_3^- equivalents referring to the highest contribution by landfilling found in a similar study in Sri Lanka (Menikpura et al., 2012). The fuel energy consumption data was obtained from Kathmandu city as the total amount of monetary value expended to purchase the fossil fuel, i.e., petrol, diesel, and kerosene combined used to collect, transport, and manage waste and multiplied to total waste handled through landfilling in each scenario.

2.3.4. Interpretation

The final stage of LCA, i.e., interpretation, includes the review of the first three phases. Comparative analysis was carried out using a spreadsheet program based on a given functional unit. The results were described as environmental impact categories backed up with justification and reasoning.

A site visit to Sisdol Landfill, the landfill serving Kathmandu from June 5, 2005, to July 2022, by the second author took place in May 2019 and the first author visited both Sisdol Landfill and the newly constructed Banchare Danda Landfill on February 21, 2023. The visits were useful to validate the existing SWM scenario for Kathmandu. In any LCA study, the final step in impact assessment is the valuation of weighting methods that do not have any formal scientific significance (Bishop, 2000; Ozeler et al., 2006), especially when the impact categories (GWP, AP, and EP) can vary and are dependent on processes, time, and local geography (Al-Salem & Lettieri, 2009). Therefore, this study was more focused on the comparison of impacts or environmental burdens by the quantity of waste managed via landfilling, rather than waste recycled, and composted for each scenario developed.

It is important to note that this paper is not meant to be conclusive but to serve as a foundation on which further research can be built. The research primarily is based on secondary data obtained from Kathmandu city, and so lacks some primary data for calculations. In addition, we wanted to examine if the model could be useful for solid waste disposal in Kathmandu even though the available data set did not include historical data concerning the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation. The literature (Bian, Chen, et al., 2022; Yaman, 2020) suggests that the missing data will have little impact on the model scenario ranking, and therefore on the SWM decision-making, which is presented in detail under subsection 4.5 later. The functional system boundary of this LCA study does not include long-term emissions from landfills, where potential emissions continue for approximately 100 years (Eriksson et al., 2005).

3. Results and discussion

3.1. Current SWM practices

Earlier efforts of SWM in Kathmandu date back to 1919 when the city first established a sanitary office (Dangi, 2009; Thapa & Devkota, 1999). Since its inception, the entity has been organizing solid waste and sanitation practices in the city and its territory (Dangi, 2009). In Kathmandu, a whistle-blow and door-to-door collection practice are in place, involving private sector operators, non-governmental organizations, and community-based organizations. Nearly all waste is collected unsorted and unprocessed, while only a small portion is source segregated (Chhetri, 2011). Unfortunately, Kathmandu has not been able to establish an appropriately engineered sanitary landfill site after the city's last landfill, Gokarna Landfill, was closed in 1996, resulting in illegal dumps and disposal along the banks of Bagmati River and Bishnumati River (Dangi et al., 2009; Tuladhar, 1996). The temporary landfill, Sisdol, when it first opened on June 5, 2005, was financially and technically supported by the Japan International Cooperation Agency, and was supposed to only last for three years (Chhetri, 2011; Dangi et al., 2009). Another temporary landfill, Aletar, located adjacent to Sisdol, was utilized until the end of 2011, Sisdol Landfill was ultimately closed after more than 17 years of its life with multiple closures and reopening in July 2022, and Banchare Danda Landfill, two km west of Sisdol, proposed as a long-term landfill with 20 years of holding capacity, came into operation also in July 2022. A field visit by the first author on February 21, 2023, affirmed that solid waste is deposited with little care and no soil cover in Banchare Danda Landfill, hazardous hospital waste can be found scattered throughout the working face of cell 1 in Banchare Danda, the two leachate treatment ponds are nearly full in capacity, the leachate recirculation unit is not functioning, and the massive concrete platform built adjacent to the landfill for waste sorting is not in operation. At any given time nearly 100 informal workers would be scavenging waste haphazardly in Banchare Danda during its operation after the waste is unloaded in the face of cell 1, putrefying garbage along with dead animals are left uncovered throughout the surface of cell 2 of closed Sisdol Landfill, and local villagers were badly impacted by odor and vector problems.

3.2. Waste generation and composition

The population of Kathmandu is 1,003,285 (CBS, 2010) and the average unit generation of solid waste is 0.17 kg person^{-1} d^{-1}. The daily waste generation was found to be 480 mt d^{-1} at the end of 2011 (KMC, 2011). Household waste comprises more than two-thirds of the total solid waste (330 mt d^{-1}) in Kathmandu and commercial, street, and nearby village waste each contributes 50 mt d^{-1}.

Understanding the quantity of waste generated and its characteristics are crucial in designing an effective SWM plan in a city. The waste generation rate and its composition vary with population growth, lifestyle choices, economic activities, and seasonal events. The Solid Waste Management Act 2011 (2021) has prescribed the separation of solid waste into at least organic and inorganic wastes. Inorganic waste can be further segregated into plastics, paper, glass, textile, metals, rubber and leather, inert materials (sand and stones), and others. The data from Kathmandu city shows that the major portion of MSW is organic waste at 63% (KMC, 2011). See Fig. 3. Plastics and paper comprise the key portions of the inorganic waste, while metals and rubber and leather each had the smallest share at about 1% of total MSW.

3.3. Waste collection

The residents of Kathmandu have one of three options to drop off their MSW: at designated areas in the city directly on the roadside, in a container, or in one of the collection vehicles in operation each morning (Larsson & Sahlen, 2009). Various types of motorized and non-motorized vehicles and equipment are used to collect the waste and subsequently transport it to the transfer station and then to the landfill (Alam et al., 2008).

The Solid Waste Management Section of Kathmandu city has 890 sweepers, 150 drivers, 38 administrative staff, 25 mechanics, 24 metro polices, four engineers, five junior engineers, two officers, a department head, and 120 other staff (KMC, 2011). Likewise, the Environment Management Department of the city has 1047 sweepers, 100 drivers, 50

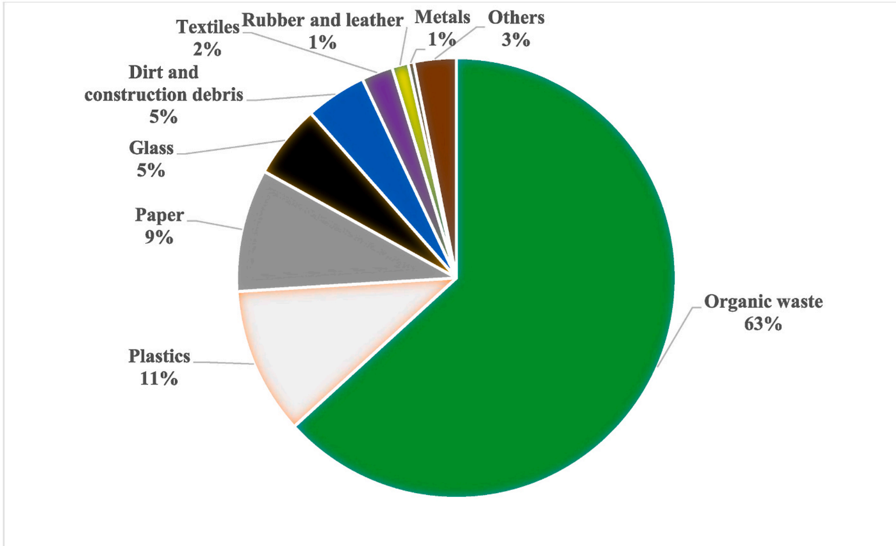

Fig. 3. Composition of municipal solid waste in Kathmandu city (KMC, 2011).

mechanics, 50 administrative workers, six community motivators, and nine engineers (Nippon Koei Co Ltd. & Yachiyo Engineering Co Ltd., 2005). (The staff may be cross-listed and counted twice as the Solid Waste Management Section is part of the Environment Management Department in the city. For details, see Fig. S2 under Supporting Information of the manuscript.) In Kathmandu, sweepers account for 51% of the city's MSW budget, and the remaining budget is allocated in the following manner: collection (33%), transfer station (3%), transportation (5%), and landfill management (8%) (Dangi et al., 2009).

Of the 461 mt d^{-1} of MSW collected (96% of MSW generated), 77.6% or 358 mt is collected from designated areas on the roadside, 13.1% or 60 mt comes from specific containers located in different areas of the city, and the remainder is gathered from door-to-door collections (KMC, 2011). However, another study (ADB, 2013) estimated a collection efficiency of 86.9% of the total waste generated. At Teku transfer station in Kathmandu city, some separation of valuable MSW is conducted, after which the MSW used to be transported to Sisdol Landfill until July 2022 and presently to Banchare Danda Landfill for disposal.

3.4. Recycling

Kathmandu city does not have a recycling operation for paper, plastics, or rubber and leather. However, the Community Mobilization Unit (CMU) of the city promotes recycling and reuse. The CMU together with Nepal Recyclable Entrepreneurs Association has established scrap collection centers where recyclable waste can be sold (Larsson & Sahlen, 2009). Informal workers locally known as *kavadiwalas* are also involved in the waste pickup at the source (Dangi et al., 2009). Using bicycles, these hawk cyclers collect waste from door-to-door in Kathmandu. While some of the traditional workers are equipped to process their recycled waste, others ship the recyclables to India for further handling (Larsson et al., 2010). The recycling activity also includes *kavadiwalas* scavenging valuable waste goods at the transfer station, streets, municipal containers, and landfill sites and then selling the goods to the recycling centers, locally known as *kavadi* shops (Dangi et al., 2009, 2017). A study (MOUD, 2015) also reported about 300 scavengers were involved in segregating the waste at the landfill site. Overall, the reuse and reprocessing of waste by local manufacturers or shipment to industries in India contribute to the recycling effort in Nepal (Dangi et al., 2009; Larsson et al., 2010). However, according to another study (Dangi, 2009), careless handling of waste occurs when personal economic benefits take priority over efficient, planned SWM. This poorly planned and executed activity inhibits the organized improvement of SWM. It is important to note that *kavadiwalas* and informal scavenging manage approximately 10% of the total MSW in Kathmandu (Bhattarai, 2003; Dangi et al., 2009). Although formal recycling is still missing in Kathmandu (Dangi et al., 2017), the MSW goes through the attempts of multi-stage material recovery from the point of generation to even after its dumped in the landfill (Parajuly et al., 2018), thus indicating a potential diversion of at least 25% of total MSW from landfills.

3.5. Composting

The Solid Waste Management Act 2011 (2021) of Nepal directs the local government to construct and operate compost plants to process organic waste. Kathmandu city neither issues directives nor operates compost plants to reduce the volume of the organic portion of MSW. However, the 19th Municipal Council meeting decided to distribute compost bins for residents at a 50% subsidized rate. It provided 1500 compost bins in 2011–12 and 1739 in 2013–14. A total of 3239 compost bins distributed for three years is inadequate when compared to over a million residents in Kathmandu at the time (MOUD, 2015). Most recent data show similar figures. In the fiscal year 2020–21, 446 compost bins were sold by Kathmandu city to its residents at a largely subsidized cost, 570 were sold in the fiscal year 2021–22, and the city is planning to distribute another 884 bins in the upcoming fiscal year. While the city claims to have distributed more than 10,000 compost bins since 2002, the numbers are still dismal with an average distribution of 500 bins a year and the fact that the city has no record of the proper use of the bins nor their conditions (Kathmandu Metropolitan City, 2022). In addition, the transfer station was built for segregating the waste collected and composting the organic waste, but it is not in operation due to managerial issues and a lack of infrastructure (MOUD, 2015).

Dangi et al. (2011) suggested considering the composting of organic waste based on the rate of waste generation and composition with a detailed study of waste management strategies. Previous studies on MSW composition have shown that organic waste makes up most of the total waste. The organic components of the waste are in a range of 60%–71% of the total MSW generated (ADB, 2013; Alam et al., 2008; Dangi et al., 2011; Karki, 2015). The studies have recommended implementing waste segregation and handling of waste at the source to divert as much waste as possible from landfills.

In developing countries, the scenarios for SWM in rural areas are equally alarming as it is in urban communities, where there is a lack of scientific strategies to manage waste (Das et al., 2019). Unlike urban areas, composting is the most practiced and accepted SWM technology in rural areas (Narayana, 2009). In many developing nations, bio-waste is considered the major fraction of the MSW stream in rural areas (Mihai & Ingrao, 2018). One of the studies affirmed that proper management of critical parameters and source segregation of bio-waste results in home composting as a more practical and economically viable option in rural areas (Van Fan et al., 2016). Currently, different modern and large-scale composting is commonly practiced in various rural areas as a part of waste management practice. Windrow composting facilitated with aeration is extensively used in vegetable culture in rural areas to recycle solid waste, i.e., both biodegradable and organic, for waste management (Gavilanes-Terán et al., 2016). Solid waste production in cities is higher than in rural areas, where rapid urbanization and lifestyle changes can alter waste production proportions. Another study indicated that 40% of the waste dumped in a landfill in city areas consists of biodegradable materials (Manios, 2004).

In brief, studies have suggested that composting of different kinds is more accepted as a SWM treatment option in rural areas (Das et al., 2019; Mihai & Ingrao, 2018). However, several energy recovery technologies, i.e., waste to energy, commercially are more prevalent and their urgency is considered in city areas not only to cope with the various environmental challenges associated with waste management but also to meet the energy demand of the global population.

3.6. Energy recovery

Energy recovery in MSW management has dual advantages: minimizes the waste landfilled and produces useful energy through incineration or bio-gasification (Trindade et al., 2018). It was suggested that MSW can be used to produce electricity through incinerators with a conversion efficiency of 20–30% (McDougall et al., 2008). Although incineration is more suitable for MSW with non-biodegradable material and low moisture content (Trindade et al., 2018), studies (LaRiviere, 2007; Shrestha et al., 2014) have recommended a method, (USEPA, 2006), to determine the heat content using the heat values of MSW components as shown in Eq. (1) in subsection 2.3.2 above. It's been realized that the power generation by burning MSW is difficult because of the variability of the waste stream composition and the moisture content. Heat generation needs to be carefully controlled to be uniform, and that is difficult with MSW.

The results suggest that the MSW of Kathmandu city has the potential to produce 9.28 MBTU of heat content, which is theoretically equivalent to 2.7 MW of electricity. See Table 1. If the organic waste is digested aerobically or anaerobically or handled with other forms of MSW management, the rest of the MSW can produce 3.98 MBTU of heat content, equivalent to about 1.16 MW of electricity, i.e., enough to light around 580 households (Energypedia, 2020; Shrestha et al., 2014).

Anaerobic digestion of organic waste combined with livestock manure can be more efficient in producing biogas. This is a sustainable and environmentally friendly energy option (Iqbal et al., 2014). Also, anaerobic digestion can yield 90.6 m^3 of methane per [US] ton of organic waste (Kuo & Dow, 2017) producing an estimated 29,103.4 m^3 of methane in ideal condition from organic portion of waste collected in Kathmandu city in a day (KMC, 2011). Collection and containment of biogas are important and expensive components of recycling, and the overall costs must be incorporated into the decision-making about the waste management processes.

Table 1
Average heat value of the dry component of MSW in Kathmandu adapted from USEPA (2006).

Dry component of MSW	Average heat value (MBTU US ton^{-1})	Average heat value (MBTU mt^{-1})[a]	MSW heat content in Kathmandu (MBTU mt^{-1})
Organic wastes	7.6	8.37	5.296
Plastics	22.6	24.91	2.690
Paper	6.7	7.38	0.666
Glass	0.1	0.11	0.006
Metals	0.7	0.77	0.003
Textiles	13.8	15.21	0.349
Rubber	26.9	29.65	0.27[b]
Leather	14.4	15.87	
Total			9.28

Note.
[a] 1 mt = 1.10231 US ton.
[b] The value of 0.27 accounts for the combined heat content of rubber and leather in Kathmandu, which was calculated using an average of the heat values of rubber and leather from column 3 of the table.

3.7. Landfilling

The landfilling of waste is one of the most common, and least expensive methods to manage MSW. The required skill levels of workers in landfills are low. Landfilling can be suitable for developing countries (Chen et al., 2016). A study (Pokhrel & Viraraghavan, 2005) reported that more than 72% of the total waste generated in Kathmandu city ends up in landfills. For landfilling to be effective, it must be done using internationally accepted safety and sanitary procedures. Kathmandu city spent three times the average cost for landfilling compared to other cities in South Asia. Kathmandu city was not able to practice standard sanitary procedures during landfilling (Dangi et al., 2009).

With the combination of the closure of a compost plant on the premises of the Teku transfer station, the banning of informal waste scavenging there, and the lack of formal recycling and material recovery; an increasing amount of MSW is ending up in landfills (MOUD, 2015). While the Solid Waste Management Act 2011 (Nepal) lists the provision to run a landfill site designed to avoid adverse impacts on the surrounding environment, the MSW in Kathmandu city was dumped into the Sisdol Landfill without appropriate mitigating measures as described earlier. The Sisdol Landfill site proposed for three years' use during the construction of a permanent landfill had operated for more than 17 years as noted above. The Sisdol Landfill lacked proper engineering design and provisions for expansion (MOUD, 2015). The site seemed to have accepted a level of MSW a lot larger than the holding capacity of 275,000 mt of MSW (Shrestha et al., 2014). The proper closure and post-closure care of the Sisdol Landfill must be addressed. Constructing any new landfill will require a design that minimizes the human and environmental impact of long-term use. Landfilling can be used in conjunction with other methods like recycling or material recovery, energy recovery, and composting to avoid adverse effects, i.e., contamination of nearby water sources and soil that can last up to 25 years after the closure of the facility (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Shrestha et al., 2014; Wichmann et al., 2006). The research reported in this paper suggests that less than 10% of the total MSW would only be discarded and landfilled (Dangi, 2009), hence would have potentially increased the life expectancy of the Sisdol Landfill by five times. The status and effectiveness of the current landfill, Banchare Danda, were mentioned in subsection 3.1 above.

4. Environmental impacts

As mentioned in subsection 2.1 above, we have developed three scenarios or SWM alternatives that are quantified according to the various impacts on the environment. These results are combined with the fuel energy consumption associated with the different scenarios presented in Table 2.

Based on the data gathered at the life cycle inventory stage, Table 2 shows the results assuming the total quantity of waste generated per year is landfilled; the next scenario, column 2, assumes that some of the waste is recycled. Column 3 includes waste that is composted. Scenario 1 represents business as usual where landfilling is the only option for the disposal of 168,265 mt of MSW per annum. The waste that can be

Table 2
Quantity of landfilled that could be recycled and composted for each of the developed scenarios.

Scenario type	MSW landfilled (mt yr^{-1})	MSW recycled (mt yr^{-1})	MSW composted (mt yr^{-1})
BAU	168,265		
Recycling	126,199	42,066	
Composting	62,258		106,007

recycled in Scenario 2 is 42,066 mt per year. The organic waste that can be used for composting is 106,007 mt annually.

Similar to Scenario 1, Mathioudakis et al. (2022) also employed subsequential modeling technique to further examine BAU, where they discovered that the scenario can have several benefits if implemented properly. In addition, the study suggested there would be significant reduction of emissions under BAU when the food waste would be source segregated. Therefore, the environmental benefits of Scenario 1 were found to be rather significant (Mathioudakis et al., 2022). MSW comprises of both biomass (food waste, paper, grass clippings, leather, etc.) and fossil fuel materials (rubber, plastics, glass, ceramics, metals, etc.). The biomass products are degradable and the fossils fuels are hard to decompose (Ayodele et al., 2018).

Like Scenario 2, a study suggested that recycling could be one of the dominant SWM methods, where the discarded waste can be recycled and reused, lowering the consumption of fossil fuels. This eventually can result in reduced GHG emissions (Shah et al., 2021). As recycling rate increases carbon emission decreases or vice versa (Liu, Tan, et al., 2020).

Composting is a widely used practice to manage organic solid waste, which can bring down landfill gas emission as it can convert the degradable waste to energy (Fadhullah et al., 2022; Mor & Ravindra, 2023). Anaerobic digestion could be the best method for decomposition of kitchen waste compared to other existing treatment options with the lowest environmental impacts and higher energy recovery (Shih et al., 2021). Keng et al. (2020) suggested that in larger scale operations, composting, being an aerobic process, will be more convenient as it will not require the advanced reduced condition. Different studies have different arguments on each of the processes of composting and landfilling; however, when these processes applied in conjunction can limit the GHG emissions with the lesser environmental impacts much like the findings of our study.

4.1. Global warming potential

The IPCC (2021) guidelines suggest that the Sisdol Landfill site can be categorized as a deep and unmanaged dumping site, and thus has a high potential for methane emissions. Furthermore, the MSW consists of a large fraction of biodegradable waste, 63% organic waste which leads to a greater share of degradable organic carbon. Also, the subtropical climate of Sisdol Landfill additionally favors methanogenesis. The IPCC (2021) waste model was used to calculate GWP as included in Eq. (2) in subsection 2.3.3 above.

Based on the characteristics of waste and the conditions of the Sisdol Landfill site, the calculated IPCC default values for Eq. (2) are: MCF(x) = 0.5 (value for partially aerobic landfill site), DOC(x) = 0.174, DOCF = 0.5, and F = 0.5. The IPCC waste model estimated 29 kg of CH_4 as the total potential methane generation from one mt of MSW landfilled (UNFCCC, 2020). The conversion factor of 21 kg carbon dioxide equivalent was used per kg of CH_4 (DEFRA, 2012). The CO_2 generation is included in subsection 4.5 below.

4.2. Acidification potential

Acidification potential is defined as a pollutant's capacity to form many H^+ ions from acidifying contaminants like H_2S, SO_x, NO_x, NH_3, etc. Which consequently oxidize to form acids with significant impacts on both flora and fauna (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). It is derived as H^+ ions produced per kg substance relative to SO_2 equivalent (Baumann & Tillman, 2004). Although the transportation factor is one of the main contributors to acidification potential, it's not considered in this study while only AP due to landfilling is considered.

A landfill model estimated that 0.65 kg of H_2S is emitted from a mt of waste landfilled (Nielsen & Hauschild, 1998). Using this model, the overall acidification potential in Sisdol is 1.22 kg of SO_2 equivalent per mt of MSW landfilled. In addition, recycled paper, cardboard, and plastics may decrease the acidification potential (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017); however, the recycling rate in Kathmandu city is only about 10% (Bhattarai, 2003; Dangi et al., 2009).

4.3. Eutrophication potential

Eutrophication can be defined as the phenomenon where excess nutrients, such as nitrogen and phosphorus species, are washed from the environment into terrestrial and aquatic ecosystems and result in algae blooms and a general increase in biomass in a waterway (Banar et al., 2009). Nitrogen, one of the major elements found in landfill waste, is considered a primary contributor to eutrophication along with phosphorus. The nitrogen is carried through leachate and runoff to the nearest water resource, i.e., *Kolpu Khola* (river). The estimated eutrophication potential for a mt of MSW landfilled is 16.42 kg of nitrate equivalent (Menikpura et al., 2012). However, the eutrophication potential can be controlled by careful engineering design of the landfill and regular monitoring of the water movement through the landfill. The goal is to prevent leachate and runoff from reaching the stream.

4.4. Fuel energy consumption

As mentioned in subsection 3.3 above about the MSW budget in Kathmandu city, the majority of fuel costs account for 49% of the budget attributed to collection, transfer and transport, and operation and management of the landfill.

The total fuel cost including diesel and petrol for the collection, transportation, and management of waste for the fiscal year 2011–12 was approximately NR 745,251 (KMC, 2011). The collection and transportation of waste does not have a fixed route but a fixed number of trips with a fixed amount of fuel (Alam et al., 2008). The figures suggest that Kathmandu city spends NR 4.42 per mt of MSW transported and landfilled for fuel cost. This amount doesn't account for the fuel charges by private companies during the collection and transportation of MSW.

4.5. Impact of variables not included in the database

We tested the hypothesis that the LCA model was not impacted significantly by the lack of data for several variables by including a wide range of values for the variables in the models from the literature.

The results of the model calculations for the three scenarios are shown in Table 3. The total values for each of the three scenarios provide a comparison of the environmental burdens and the total cost of fuel consumed during the collection, transportation, and management of MSW. Table 3 also provides the results of including a wide range of values from the literature for variables that were not in the database.

The composting scenario shows the least impact on the environment based solely on database values.

Adding the high and low values from the literature in several combinations to the calculations shows minimal impact on the scenario ranking of environmental input.

5. Policy implications

A goal of creating effective public policy is to arrive at a decision that

Table 3
Calculations for ranking the three scenarios, where the totals from the LCA models are in bold font.[a]

Results from 3 scenarios without missing variables

Scenarios	GWP (kg CO2 eq. mt MSW-1 landfill-1 yr-1)	AP (kg SO2 eq. mt MSW-1 landfill-1 yr-1)	EP (kg NO3- eq. mt MSW-1 landfill-1 yr-1)	FEC (total fuel consumed in NR mt MSW-1 landfill-1 yr-1)	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**

Results from 3 scenarios with high-range literature values for indirect and direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	High Indirect	High Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	7.38 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	7.38 E+04	8.03 E+05	8.19 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	7.38 E+04	8.03 E+05	**3.99E + 07**

Results from 3 scenarios with high-range literature values for indirect and low-range values for direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	High Indirect	Low Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	7.38 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	7.38 E+04	5.55 E+02	8.11 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	7.38 E+04	5.55 E+02	**3.91E + 07**

Results from 3 scenarios with low-range literature values for indirect and high-range values for direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	Low Indirect	High Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	2.88 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	2.88 E+04	8.03 E+05	8.18 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	2.88 E+04	8.03 E+05	**3.99E + 07**

Results from 3 scenarios with low-range literature values for indirect and high-range values for direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	Low Indirect	Low Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	2.88 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	2.88 E+04	5.55 E+02	8.10 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	2.88 E+04	5.55 E+02	**3.91E + 07**

Note.
[a] The table shows the results from calculations for the ranking of the three scenarios without the variables that were missing from the data set, to compare with the results from the LCA scenarios that included a wide range of literature data for the missing variables. The models, scenarios, and totals are in bold font. The values used for the direct–low range came from Yaman (2020). The values for the direct–high range and indirect-high range are from Bian, Chen, et al. (2022).

combines environmental, economic, and social components (Al-Salem & Lettieri, 2009). There are few, if any, rigorous LCA studies that have been conducted in Nepal, particularly concerning SWM; therefore, such studies are crucial to establishing an informed understanding of environmental burdens and costs associated with managing MSW in Kathmandu city. A publication (Khandelwal, Thalla, et al., 2019) identified the lack of LCA in SWM studies in the central region of India and emphasized the importance of social, economic, and psychological factors in SWM. Another publication (Khandelwal, Dhar, et al., 2019) mentioned the necessity of using an LCA to come up with an SWM hierarchy and reported that there has been only one LCA study in Nepal. Even then, the study (Singh et al., 2014) is slightly outdated and stressed landfilling heavily and left room for other options. Our study has the objective of setting a foundation for further and more intensive, extensive, and complete efforts to produce an LCA that can be used for MSW management decision-making in Nepal. Such studies will also lead to the establishment of databases that will aid decision-making processes and help elected officials take suitable environmental measures.

Additionally, the appropriate policy influences the residents' behaviors which requires them to have the proper knowledge of waste classification and environmental protection at the regional level (Villalba et al., 2020). The waste classification behavior will change residents' attitudes and assist them in characterizing and classifying waste before disposal, arousing awareness towards environmental protection (Liu, Osewe et al., 2020). Various factors like socioeconomic, institutional, temporal, and cultural aspects, etc. Can also affect waste quantity management and composition at regional levels as it varies accordingly based on locations (Villalba et al., 2020). A study performed in Jiangsu, China demonstrated the essence of education toward environmental protection as it pertains to SWM in rural areas (Liu, Osewe et al., 2020). Also, environmental protection awareness incorporates the benefits of classifying and collecting waste at the regional level on a daily basis (Fami et al., 2019; Mihai & Grozavu, 2019).

There are other recent studies that have similar policy objectives. For example, it's been suggested that recycling papers, plastics, metals, and glass can reduce the GWP by 50% as using recycled materials to produce plastics and papers consume less energy than producing them using raw materials (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). Also, recycling replaces raw materials and advances environmental sustainability (Nabavi-Pelesaraei et al., 2020).

We have included the emissions from the collection, transportation, and management of waste in landfills (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017) by using values found in the literature. We examined the effects of the emissions from the collection, transportation, and management of waste in landfills by executing the LCA model with a range of values found in the literature. The addition of the literature values for the missing data had little impact on the ranking of the scenarios based on their emissions to the environment. Even without performing an LCA, it is obvious that MSW management problems can be overcome by executing better landfill design; methane extraction from landfills; and use of methane as an alternative to fossil fuel.

In the past, people dumped their garbage and trash on the street or on the floodplains of the Bagmati River, in Kathmandu. The waste would be washed down to the Bagmati River flood plains. Often, pigs were released on the flood plains to separate the garbage from the trash. Pig manure combined with MSW contributed to the severe pollution that was apparent in the river. Sustainable SWM done in the most efficient, economical fashion would have dramatic impacts on the environmental conditions in Kathmandu.

The results of this study indicate the need for sustainable SWM in Kathmandu, that the approach must consider a conjunctive disposal system with composting and landfilling to reduce environmental impacts (AP, EP, and GWP). This excludes external factors like the inefficient collection system, low public participation, landfill location, and operational improvements. A well-thought-out integrated planning and capacity-building initiative in SWM backed by steady financial support could help alleviate the waste management and pollution problems in Kathmandu (Gautam, 2011). Additionally, the use of LCA along with proper waste characterization, recycling, and reduction—including reuse and composting for different types of wastes—and appropriate landfilling is crucial for a successful SWM operation.

6. Conclusions

This study was conducted to evaluate the use of LCA for SWM decision-making for Kathmandu city. An LCA model was run for each of three alternative SWM scenarios. LCA models were run with a wide range of literature values for missing data from the Kathmandu city data set. This is one of the few studies conducted for Kathmandu city using LCA.

The major findings of the study include.

1.) The current practice or Scenario 1 results in the highest global warming potential and is considered harmful in terms of other environmental impacts; 2.) Scenario 3 is the best alternative for lowering the contribution to climate change, eutrophication potential, and fuel energy consumption. This results in reduced environmental impacts and lower operating costs; 3.) Scenario 2 gives environmental impacts in between scenarios 1 and 3, thus becoming the second-best option; and 4.) Direct emissions from composting, energy recovery costs, and indirect emissions from collection and transport had little impact on the ranking of the environmental mitigation scenarios.

The findings suggest that Scenario 3 had the lowest potential for environmental impacts and is more cost-effective in terms of fuel energy consumption compared to the other scenarios. The outcome is influenced by the large quantities of organic waste that can be composted, resulting in the reduction of GWP. Overall, the results support the proposition that LCA can be applied to an integrated SWM operation as an environmental tool to support decision-making processes and the development of policy in Nepal.

7. Recommendations

These are the recommendations for sustainable SWM in Kathmandu based on our preliminary study.

a. The Solid Waste Management Section in Kathmandu city can focus on formally organizing recyclable materials recovery to help reduce the amount of waste disposed of in landfills and save landfill space, which will reduce the amount of national income spent on landfilling and reduce environmental burdens.
b. Because of the high quantities of organic waste in MSW in Kathmandu, almost two-thirds of the total waste, converting this waste to compost and biogas through aerobic and anaerobic processes may minimize the quantities of waste being deposited in landfills. This approach should be a priority.
c. The approach taken in our study should serve as an example for the development of appropriate integrated SWM options suited for local conditions. This approach has the potential to aid in the development of a successful implementation of waste management strategies, not just in Kathmandu, but in other Nepali municipalities as well.

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.habitatint.2023.102895.

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Sabbatical Leave Application

College of Social Sciences

Submitted to

Dr. Segun Ogunjemiyo
Interim Dean, College of Social Sciences
California State University (CSU), Fresno

Faculty Member

Mohan B. Dangi

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Section 1. The Proposal

I have been awarded the 2021 Fulbright U.S. Scholar award for teaching and research in Nepal. The award is one of two given to U.S. scholars for important research and technical services in Nepal by the U.S. Department of State's Bureau of Educational and Cultural Affairs. (Please see Appendix A for the Fulbright U.S. Scholar award letter.) To fulfill this obligation as a representative of California State University (CSU), Fresno, to further develop my research skills using life cycle assessment (LCA) methods, to make an important contribution to the well-being of Nepal, including an understanding of the impacts of the massive 2015 Nepal earthquake that killed nearly 9,000 people, I intend to fulfill the following three objectives during my proposed sabbatical leave in the Academic Year 2022-2023:

1.) Design, develop, and teach an urgently needed Introduction to Environmental Engineering course at the Central Department of Environmental Science (CDES), Tribhuvan University (TU), Kirtipur, Nepal to fill curricular gaps and deliver the course online, essential during current pandemic conditions.

2.) Further advance research using LCA for solving problems concerning municipal solid waste (MSW) management in Kathmandu, Nepal.

3.) Publish at least one manuscript covering LCA of MSW and/or earthquake recovery work covering the 2015 Nepal earthquake that was partially funded by the CSU, Fresno community.

My educational background, teaching, and extensive course development experience have prepared me to address critical curricular gaps at CDES. Initially, I will design an Introduction to Environmental Engineering course that meets local Nepali needs, following the rules necessary to reduce the risk of the pandemic. A unique component of the course will be material to introduce students to concepts in environmental entrepreneurship. There also will be coverage of the topic of sustainability in the course along with its traditional contents. Given that CDES follows two six-month-long semesters starting in September/October and March/April, I would like to deliver the face-to-face instruction of the course from mid-August through February for Master of Science (MSc) third-semester students. (The two weeks in August will be used for relocation and preparation of the course and any essential orientation in Kathmandu.) A detailed timeline is provided in Table 1 at the end of this section. This will be the first course of its kind as CDES (2017) does not have courses in environmental engineering nor entrepreneurship. The course will be divided into five parts: a) basics of environmental science and engineering, b) land-based pollution, c) water quality and quantity, d) air pollution and climate change, and e) entrepreneurship, sustainability and special topics. Seven homework assignments, five videos that feature efficacious environmental practices, a case study report, student presentation and peer evaluation, a field visit tied to laboratory analysis, and three exams will be used to evaluate students.

Two to three well-respected guest speakers will be invited to discuss relevant topics. The case study will be a group effort to encourage teamwork and replicate real-world practices. The bulk of the rest of the work will be individual. The delivery of the course will last six months, the research portion of the study will take three months from March through May, and online delivery of the course will occur during the second semester beginning March together with a Nepali faculty. By involving the local Nepali faculty early on in the design and delivery of an online course, I will help train the faculty member, build the capacity of the host institution, and aid in the transition and responsibility of teaching the course to the university after I complete my sabbatical leave. (Please see Appendix B for the letter of support from Tribhuvan

University.) I was awarded eScholar and DISCOVERe grants at CSU, Fresno to convert my Environmental Pollution course into an online course and Global Environmental Change course into a tablet course (CFE, 2021). This experience helped me to garner the knowledge and experience to deliver the course digitally using Blackboard or Canvas learning management systems. I was one of the few CSU, Fresno faculty who took advantage of the advanced online instructional training through the Virtual Summer Institute in summer 2020. I can assist the training of CDES faculty to deliver online teaching at a time when regular instruction is at standstill in Nepal due to the global pandemic.

I have successfully developed Environmental Policy Management, Environmental Impact Assessment, and Introduction to Environmental Entrepreneurship courses at CSU, Fresno and two study abroad courses at CSU, Fresno and the University of Wyoming (UW), and possess technical background with first Master's degree in Environmental Science and Engineering and Professional Engineering (PE) license in environmental engineering. Therefore, I have the qualifications to design and deliver the Environmental Engineering course. Furthermore, I have been teaching a very popular general education course at CSU, Fresno, Environmental Pollution, that has similar content and approach to undergraduates. I have co-taught Earth and Environmental Systems and Environmental Engineering Field Session courses at the Colorado School of Mines and have prior experience in design and delivery of K-12 Renewable Energy curriculum and Master of Science degree in Renewable Energy Engineering and Diploma course in Environmental Engineering in Nepal all funded by the U.S. government, which provide the needed training.

I plan to begin the research component of the proposal by gathering yearly data on the disposal of MSW in Kathmandu city. MSW is collected daily by city workers, community-based organizations (CBOs), or non-governmental organizations (NGOs) and is brought to Teku Transfer Station and deposited in Sisdol Landfill (Dangi, 2009). The data on waste collected/managed daily/monthly at Teku and Sisdol will be examined for three years (2018-2020), LCA methods will be applied, and alternative solid waste management (SWM) scenarios will be developed for Kathmandu. The research objectives in Kathmandu include 1) analyze current MSW stream characteristics and estimate the amount of waste generation; 2) examine the cost of current SWM; 3) understand how landfilling compares with other options of SWM; 4) derive the environmental cost of SWM; and 5) suggest alternative SWM and its effectiveness. I have spent a considerable amount of my time and effort in the past 17 years studying SWM in Nepal. Previous studies have revealed that earlier reforms in SWM have failed and there is a need to find a local solution for it (Dangi et al., 2015).

The research methods will include multiple visits to the Kathmandu city office to collect logs of waste pick up and disposal records, understand how Teku Transfer Station and Sisdol Landfill function, and obtain a basic fact sheet of SWM data for the three years and applicable SWM publications. Interviews will be conducted with the chiefs of the SWM Section and Environment Department of the city, landfill manager at Sisdol, the official in charge of SWM at Ministry of Federal Affairs and General Administration, and relevant CBO and NGO staff. Other publications will be accessed using the e-library of CSU, Fresno. The basic fact sheet of SWM received for three years will be authenticated with what is being recorded daily/monthly at Teku and Sisdol. The CBO and NGO reports could help us recognize how overall solid waste is managed. Interviews with city officials could provide information on SWM at the neighborhood, ward, and city-level; the difficulties they face; and any future SWM plans. Conversation with Ministry staff can offer national short- and long-term plans for SWM. The literature review will provide current trends in MSW generation, composition, and practices. I will then use an LCA tool to identify alternative SWM scenarios, i.e., business as usual, including collection, transportation, and landfilling; energy recovery with recycling; and conjunctive disposal comprising composting and landfilling (McDougall et al., 2001). The findings will be compared to other studies (Iqbal et al., 2020; Nabavi-Pelesaraei et al., 2017a, 2017b, and 2020; Silva et al., 2021; Taskin and Demir, 2020). Subsequently, environmental impact on air, land, and water will be calculated. The data will be collected from March through May 2023, analyzed, and presented in May-June 2023 in a seminar at CDES and three cities (Kathmandu and one each in eastern and western Nepal). The writing of a manuscript will take place in July-August 2023 and will be submitted to the *Waste Management* journal. I will also disseminate the results in the Global Waste Management Symposium 2024.

The earlier work I took part in during my Fulbright Specialist assignment in 2018 in Nepal (Dangi et al., unpublished manuscript) and the research in LCA of green waste in Fresno performed by my students, offer additional bases for the proposed research. The use of stratified cluster sampling tools to understand waste stream characteristics at the source of generation that was tried and tested in Kathmandu (Dangi et al., 2011) was successfully used to learn the facts about green waste and its impacts on the environment in Fresno (Dangi et al., 2014; Mey et al., 2012). The proposed research in LCA of MSW in Kathmandu is an important extension of our work in LCA of green waste in Fresno and this displays an example of how a study from a locale could be applied to a similar problem to other locations. Both Fresno and Kathmandu seem to be benefiting from our research (Mey et al., 2012; Dangi et al., unpublished manuscript). The extensive data collection and field visit requirements won't be possible to execute during a normal semester and the academic yearlong sabbatical leave provides appropriate timing to complete the study.

The LCA has been a useful tool to evaluate the performance of MSW management (Assamoi and Lawryshyn, 2011; Dangi et al., 2014). It covers full "cradle to grave" impacts of a product or service (Barton et al., 1996) and can be valuable to assess environmental burdens and potential effects (Khorasani et al., 2012). Rapid economic development and population growth have accelerated the generation of MSW in many developing countries, thus demanding an effective and reliable SWM strategy (Tang et al., 2018). Kathmandu is plagued with haphazard handling of MSW, including indiscriminate dumping of waste on the street, in open public spaces, and on the banks and in the beds of holy rivers. The waste clogs the city's limited drainage systems, contaminates surface and groundwater, encourages the proliferation of insects and rodents, and poses a risk of direct exposure (Dangi, 2009; Gautam, 2011). Such practices could present serious and everlasting threats to public health and the environment in the least developed countries (Alamgir et al., 2005; Mali and Patil, 2018). Kathmandu city has experienced a population growth rate 3.4 times larger than Nepal's national annual rate between 2001 and 2010 (CBS, 2010). This overpopulation, combined with hasty development, has created unparalleled pressure on the city's constrained resources and infrastructure, presenting even larger SWM problems (Dangi, 2009; Dangi et al., 2006; 2009, 2015, and 2017). Kathmandu city has attempted to reorganize its SWM several times, but it continues to face major challenges (Dangi, 2009; Dangi et al. 2009 and 2015). Application of LCA along with proper waste characterization, recycling and reduction, including reuse and composting for different types of wastes, and appropriate landfilling is crucial for a successful SWM. Khandelwal et al. (2019a) identified the lack of LCA in SWM studies in the central region of India and emphasized the importance of social, economic, and psychological factors in SWM. Khandelwal et al. (2019b) mentioned the importance of LCA to come up with the SWM hierarchy and reported that there has been only one LCA study in Nepal, i.e., Singh et al. (2014). Even then, the study is slightly outdated and stressed landfilling heavily and left room for other options. The proposed study, therefore, aims to fill the void.

My earlier MSW study in Kathmandu was the foundation for our green waste work in Fresno. The research using LCA to study green waste in Fresno serves as a foundation for our proposed research in Kathmandu and eventual publication.

In 2015, the Fresno State community, including President Castro, provided support for the relief of the massive Nepal earthquake and part of that support was used to help rebuild a primary school in the Rasuwa district (Fresno State, 2015a and 2015b). While delivering and executing the support, I also conducted a preliminary survey of the area to understand the impact the earthquake has had on the livelihood and environment. Therefore, from July to August of 2023, I plan on drafting at least one manuscript covering the application of LCA and/or the earthquake work. I have compiled and analyzed some earthquake data. However, it has been very difficult for me to find time for completing a manuscript for publications during regular semesters as this will demand more uninterrupted time than what’s possible during normal academic years.

Table 1. Schedule of proposed activities to be performed.

Period	**Location**	**Activities**
August 17- 31, 2022	Fresno, California and Tribhuvan University, Kirtipur, Nepal	Relocate to Kirtipur, Nepal and prepare for the new course, Introduction to Environmental Engineering, and take part in any essential orientation.
September 1, 2022-February 28, 2023	Tribhuvan University, Kirtipur, Nepal	Design, develop, and teach an Introduction to Environmental Engineering course at the Central Department of Environmental Science, Tribhuvan University.
March 1-May 31, 2023	Kirtipur and Kathmandu, Nepal	Visit Kathamndu city office to gather annual MSW data for years 2018 through 2020, conduct interviews, and tour Teku Transfer Station and Sisdol Landfill sites to understand current SWM practice and triangulate waste data through daily/monthly logs.
March 1-August 31, 2023	Kirtipur, Nepal	Online delivery of the course begins together with a Nepali faculty, who will take over after me at the end of the academic year in May 2023.
May 1- June 30, 2023	Kathmandu and two other cities in Nepal	Preliminary results will be presented in a seminar at Tribhuvan University and three cities (Kathmandu and one each in eastern and western Nepal).
July 1-August 31, 2023	Kirtipur, Nepal and Fresno, USA	The writing of a manuscript will take place and the paper will be submitted in the *Waste Management* journal.

Section 2. Benefits to you as a Faculty Member

In the last thirteen years as a faculty member at CSU, Fresno, I have advanced my earlier research in solid waste into the life cycle analysis of the green waste with a focus in Fresno. This work was completed through the assistance of my students. I developed eight courses to meet the changing curricular needs and expectations of our students at CSU, Fresno, TU, and UW; however, I have not had the opportunity to deliver a more robust course comprising environmental engineering and hands-on laboratory techniques. My experience teaching the Environmental Pollution course to students from various disciplines at CSU, Fresno has provided much-needed footing to craft such a course. The water quality work performed by the College of Social Sciences (COSS) funded grant, *Environmental and Water Studies Project*, has further aided my fieldwork capability and management tools to my theoretical knowledge and I hope to utilize it in bench-scale experimentation at TU.

I have published or have had accepted in journals and proceedings twenty-eight manuscripts. None of them cover earthquake-related work. I have three graduate degrees in the areas of water and wastewater treatment engineering, systems engineering, and solid waste engineering and policy with a PE license. Therefore, I should quickly be able to familiarize myself with the modeling tools required for earthquake work. My established knowledge in interpreting qualitative information and combining it with quantitative measurements will also be of assistance in the collection and analysis of information related to earthquakes and their impact on the environment. The experience derived from enhanced laboratory analysis, modeling, and application of extensive field techniques and methods during the sabbatical leave will offer a rich context for the delivery of Environmental Pollution and other courses at CSU, Fresno upon my return. The exposure and training of MSW workers in three cities of Nepal under the Fulbright award will provide the perspective and knowledge of the needs of localities in the area of environmental planning and management needed in the Department of Geography and City & Regional Planning since the Department has just embraced Planning degrees in the curriculum.

My current public service to the National Academies of Sciences, Engineering, and Medicine and the United States Agency for International Development as a Jefferson Science Fellow has provided me a global opportunity to take the classroom experience and share novel ideas that have come out of our green waste work in the Central Valley. The training I am receiving as a science diplomat covering humanitarian waste issues internationally and combining it with emerging topical knowledge in water and waste from Fresno county will be extremely valuable to further develop and deliver a course that combines environmental science and engineering. Thus far I have offered or created curricula mostly in human and environmental geography, but lack the opportunity to offer courses in environmental methods and techniques. It is expected that with added knowledge and experience in current laboratory and field methods for water, waste, and air topics, I will be able to improve the organization of curricula by contributing to the development of techniques and methods courses in the Department of Geography and City & Regional Planning. Using the funding from the *Environmental and Water Studies Project*, I have already purchased two important water quality monitoring equipment (Horiba U-50 Series Multi-Parameter Water Quality Meter and Hanna - DO Meter with Barometer with 4mt cable probe, carrying case). It is very likely that the knowledge acquired in methods and techniques in Nepal will lead to a better application of advanced methods of teaching at CSU, Fresno as I secure more equipment through future grants. The design and development of an in-person course and subsequent conversion into online instruction in Nepal will solidify my abilities to teach distant/online learning to a variety of groups and students from a multi-ethnic background in Fresno. I have an extensive track record for publishing and disseminating new knowledge in the field of solid waste. This experience will permit me to offer upgraded techniques and methods to attract grants for tackling local pollution problems in the San Joaquin Valley and contribute more to the discipline via future publications.

Section 3. Benefits to the University

I believe my proposed sabbatical leave will yield the following benefits to the department, college, and university:

1.) This will help enhance the ability to analyze environmental pollution problems using state-of-the-art techniques and cutting-edge technology in the Department of Geography and City & Regional Planning.

2.) The outcome of the leave will permit the creation of areas of emphasis in environmental methods and techniques in the Department of Geography and City & Regional Planning.

3.) This will attract more students studying environmental methods and pollution science in the Department of Geography and City & Regional Planning. (Please see Appendix C for the letter of support from the chair of the Department of Geography and City & Regional Planning.)

4.) Future publications will add new knowledge to the application of LCA in MSW management in low-income countries, it will expand our knowledge of how short- and long-term impacts of natural hazards, earthquakes affect people's livelihood and the environment, and it could bring additional limelight to the Department of Geography and City & Regional Planning.

5.) The future curriculum development effort related to the topic will help me to develop techniques and methods related courses.

6.) The experience of the sabbatical could enhance the image of the COSS in leading efforts in sustainability practices by utilizing proper techniques in addressing a variety of environmental problems, e.g., solid waste, wastewater, and water within the University community.

7.) The results of the sabbatical will provide more visibility to CSU, Fresno among other universities nationally and internationally. The efforts will help lead an instructional paradigm shift by delivering a new online course in a developing country much needed during the current pandemic.

8.) The collaborative work that I will perform with Tribhuvan University, three Nepali cities, and the Fulbright Foreign Scholarship Board will increase the profile of CSU, Fresno among national universities.

9.) Since the COSS (2021) takes pride in its mission to "teach students to think clearly, critically, and analytically; this allows students to engage in the solution of complex social problems", I believe the experience derived from the sabbatical will enable me to offer much needed critical and analytical problem-solving skills among our diverse student body.

10.) The strategic plan of Fresno State (2021) is engagement in the community, commitment to development, and providing solutions to the problems and issues of the Central Valley of California. The experience, therefore, directly aligns with the priorities of the university's strategic plan. It has the potential to offer the students training and knowledge of best practices. I will be able to teach the students with improved and updated skills upon my return. The university will gain an innovative program fortified with high-impact experiences, a potential for learning, and increased opportunities for lifelong success.

Section 4. Previous Leaves

Please see Appendices D and E for a copy of the report from the last sabbatical leave and the product of the leave, respectively.

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APPENDIX A

Fulbright U.S. Scholar Award Letter

APPENDIX B

Letter of Support from Tribhuvan University

APPENDIX C

Letter of Support from the Chair of Department of Geography and City & Regional Planning

APPENDIX D

A copy of the Report from the last Sabbatical Leave

APPENDIX E

Copies of the two manuscripts published as a result of the last Sabbatical Leave

FULBRIGHT FOREIGN SCHOLARSHIP BOARD

FULBRIGHT

April 15, 2021

Dr. Mohan Dangi
11375 North Via Napoli Drive
Fresno, CA 93730-8822
United States

Dear Dr. Dangi:

On behalf of the Fulbright Foreign Scholarship Board, I am pleased to congratulate you on your selection for the Fulbright award to Nepal for academic year 2021-2022. Our presidentially appointed 12-member Board is responsible for supervising the Fulbright Program worldwide and approving the selection of all Fulbright recipients. Your grant is a reflection of your leadership and contributions to society and is made possible through funds appropriated annually by the U.S. Congress and, in many cases, by contributions from partner countries and private parties.

The Fulbright Program is devoted to increasing mutual understanding between the people of the United States and the people of other countries. Fulbright is the world's largest and most diverse international educational exchange program. As a grantee, you will join the ranks of many distinguished program participants. Fulbright alumni have become heads of state, judges, ambassadors, cabinet ministers, CEOs, and university presidents, as well as leading journalists, artists, scientists, and teachers. They include 60 Nobel Laureates, 88 Pulitzer Prize winners, 75 MacArthur Fellows, and thousands of leaders across the private, public and non-profit sectors. Since its inception in 1946, more than 400,000 "Fulbrighters" have participated in the Program.

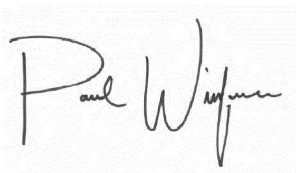
2021 marks the 75th Anniversary of the Fulbright Program. Celebrations throughout the year will highlight the impressive accomplishments and legacy of the program and its alumni over its first 75 years, both in the United States and around the world. A dedicated 75th anniversary website (www.fulbright75.org) will be updated throughout 2021 to showcase anniversary events and to facilitate ongoing engagement. I encourage you to engage through the "Get Involved" section on the website, and to join anniversary celebrations in your region, either virtually or, if possible, in person.

Your award remains contingent upon several factors. Among these are obtaining a secured placement at an institution in your host country, official research clearance from the host country (where applicable), satisfactory medical clearance, and a visa, if required. You will receive additional information on your award shortly from the Fulbright Commission or the Institute of International Education/Council for International Exchange of Scholars (IIE/CIES). After you receive your grant documents, you must sign and return them as instructed. If you have any questions, please contact your program representative at IIE/CIES.

The Fulbright Program's goal of developing international understanding depends on you and your commitment to establishing open communication and long-term cooperative relationships. As a Fulbright participant and a representative of your country, you will have the opportunity to work collaboratively with international partners in educational, political, cultural, economic, and scientific fields. We also hope you will engage in your local community while on your Fulbright exchange. In so doing, you will exemplify the qualities of service, leadership, and excellence that have been hallmarks of this Program since it began.

The United States Department of State's Bureau of Educational and Cultural Affairs, which oversees Fulbright Program operations throughout the world, joins the Board in congratulating you. We hope your Fulbright experience will be deeply rewarding professionally and personally, and that you will share the knowledge and experience you gain with many others throughout your life.

Sincerely,



Paul Winfree
Chair

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TRIBHUVAN UNIVERSITY

Central Department of Environmental Science

Tel No: 4332147
4332711

Kirtipur,
Kathmandu, Nepal

Central Department of Environmental Science
Kirtipur

Dr. Michelle Calvarese
Professor and Chair
Department of Geography and City & Regional Planning
California State University, Fresno

September 9, 2021

Re.: Letter of Support for Dr. Mohan B. Dangi for his Sabbatical Leave in AY 2022-2023

Dear Professor Calvarese,

I am writing this letter of support in extending our profound interest to host Prof. Mohan B. Dangi during his proposed sabbatical leave in AY 2022-2023 at the Central Department of Environmental Science (CDES) in Tribhuvan University (TU), Kirtipur, Nepal. As you may already know that Prof. Dangi has been granted Fulbright U.S. Scholar award to design and deliver an Introduction to Environmental Engineering course and also offer it online at CDES as well as to research life cycle assessment (LCA) of municipal solid waste (MSW) management in Kathmandu. Given Dr. Dangi has been assisting CDES and TU faculty since 2010 in curriculum development and creating opportunities for our students to work together with his study abroad students, I am very pleased to host Dr. Dangi both for his Fulbright U.S. Scholar award and for the sabbatical leave in AY 2022-2023. During his stay at CDES, we will afford him an office, laboratory facility, and access to field locations for the field trip to his students. In addition to developing and delivering the course to our MSc third semester students for in-person and online instruction, we anticipate Dr. Dangi to train our faculty about the online delivery, organize a biweekly seminar in his field of expertise to bring key individuals covering waste and sustainability topics. The CDES will provide student assistants to help him conduct LCA of MSW management in Kathmandu. The field assistants will be paid by the CDES and they will help him in data collection, assist with interviews, and keep field notes required for the research. We also anticipate that Dr. Dangi will deliver three seminars covering his findings one each in Kathmandu and two other cities of Nepal.

Since Dr. Dangi has already served as a visiting faculty in TU, this makes it easier to organize activities for his proposed visit. We are excited about his sabbatical stay in CDES and wish him the best of luck.

Thank you and please feel free to write me directly if you have any questions about this letter of support and arrangement for Dr. Dangi's sabbatical period in Nepal.

Sincerely,

Kedar Rijal, PhD, Professor
Email: krijal@cdes.edu.np

FRESNO STATE
College of Social Sciences

Dr. Segun Ogunjemiyo
Interim Dean
College of Social Sciences, California State University, Fresno

September 14, 2021

Subject: Letter of Support for Dr. Mohan B. Dangi's Sabbatical Leave Application

Dear Dr. Ogunjemiyo,

As a chair and colleague of Dr. Mohan B. Dangi, I am very pleased to write him a letter of support for his sabbatical leave application for AY 2022-2023. I have observed Dr. Dangi's progress since he was first appointed as a tenure-track assistant professor in the Department of Geography and City & Regional Planning. He has worked himself up to earn tenure and full professorship rank over the years. He has been particularly very successful in developing curriculum to meet changing needs of the students and department. He developed eight courses for Fresno State, University of Wyoming, and Tribhuvan University (TU). Most recently his work has been recognized by two Fulbright awards, the Fulbright Specialist Award in 2017-2018, and presently the Fulbright U.S. Scholar award. In addition, currently, he received the prestigious Jefferson Science Fellowship from the National Academies of Sciences, Engineering, and Medicine. All of this is an example of his commitment to his discipline and service to the Department and the University community. Since Dr. Dangi has already been granted the Fulbright U.S. Scholar award to Nepal and he is proposing to do his sabbatical leave coinciding with the award, this to me is an example of an unexpected opportunity that puts our Department and the College on top of many other nationally ranked universities. As such I fully support Dr. Dangi's sabbatical leave for AY 2022-2023 as he plans to develop and deliver an Introduction to Environmental Engineering course for in-person and online delivery at Tribhuvan University, Nepal, research life cycle assessment (LCA) of municipal solid waste management (MSW) in Kathmandu, and complete a manuscript covering the LCA study or his earthquake work in Nepal.

From the departmental perspective, his proposed work will help him enhance the ability to analyze environmental pollution problems using state-of-the-art techniques and cutting-edge technology as he teaches a brand new course in TU covering recent development in environmental science and engineering. His ability to transform the lessons from his current Environmental Pollution course at Fresno State to an Introduction Environmental Engineering course at TU and bring that back to our classroom will upgrade his skills in environmental methods and techniques areas in the Department. Eventually, students will be attracted to his environmental methods and pollution science offerings in the Department. Because of his publication record and resiliency, I am hopeful that the future publication from the sabbatical leave will add new knowledge in the application of LCA in MSW management in a low-income country and/or the short- and long-term impact of natural hazards, earthquakes, have had on people's livelihood and the environment and it could bring additional limelight to the Department.

These are just a compilation of a few things that Dr. Dangi could bring from this sabbatical leave to the Department and I am very excited about his proposed work as he represents our Department and Fresno State internationally. I wish him the very best for his sabbatical application. Please let me know if you have any questions.

Sincerely,

Michelle Calvarese, Ph.D.
Professor and Chair

Department of Geography and City & Regional Planning
California State University, Fresno
2555 E. San Ramon M/S SB69 • Fresno, California 93740-8034

P 559.278.2797 **F 559.278.7268**

Sabbatical Leave Report: Fall 2015

College of Social Sciences

Final Report Submitted to

Dr. Michelle Denbeste
Interim Dean, College of Social Sciences
California State University (CSU), Fresno

Faculty Member

Mohan B. Dangi

Contact Information

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March 18, 2016

Project Summary

Faculty member, Dr. Mohan B. Dangi was granted a sabbatical leave in fall semester of 2015 with following two objectives:

1.) To complete at least one manuscript on the work, *Life Cycle Analysis of Green Waste in Fresno*, *California*, carried out by Dr. Dangi and seven Geography, Biology, and Earth and Environmental Science students and the study of household solid waste conducted in Ghorahi Municipality, Nepal for publications; and
2.) To sharpen teaching and research skills of Dr. Dangi in the areas of water quality, primarily examination of low-cost water treatment techniques at the University of Wyoming and Tribhuvan University (TU), Nepal.

Completed Activities

Dr. Dangi intended to have at least one manuscripts completed during his sabbatical period. In the end, Dr. Dangi has submitted a manuscript that is currently being reviewed by *Environmental Science & Policy* journal for publication and another manuscript is being submitted to *Global Environmental Change* journal. The details of the manuscripts are provided below:

1.) Environmental policy analysis of waste management in Kathmandu, Nepal. (Submitted).
2.) Impacts of Climate Change on Agroecosystems and Livelihoods in Annapurna Conservation Area, Nepal. (Being submitted).

Given three of Dr. Dangi's former students (Leonel Campos, Rameshwor Kaphle, and Erika Mey) were out of country and they were running behind in analyzing the data, it was decided to focus in these two papers instead of life cycle analysis of green waste in Fresno, California and household solid waste study in Ghorahi, Nepal.

Regarding the visits to Wyoming and Nepal, they took place in October 2015 at the University of Wyoming and June-July 2015 to Nepal. While in Wyoming, Dr. Dangi had opportunity to work with Professor Peter D. Stahl instead of Professor Michael A. Urynowicz who was also in sabbatical leave. While in Nepal, Dr. Dangi was able to work with Tribhuvan University students to examine the impact of earthquake in livelihood and environment in Rasuwa district of Nepal. In addition, he met Professor Kedar Rijal and discussed about the possibility to extend the Rasuwa study involving students from CSU, Fresno and TU. Although additional visits to Wyoming and Nepal could not be materialized because of financial limitations, Dr. Dangi conducted his work in water quality treatment via literature survey and by reviewing relevant materials (*Wastewater Engineering: Treatment and Resource Recovery;* and *Environmental Engineering Reference Manual*).

Other Achievements

Dr. Dangi attended and/or presented at the following national and international venues during his sabbatical leave:

1.) *Life cycle assessment of green waste in Fresno, California*. Association of Environmental Engineering & Science Professors Conference. Yale University, New Haven, CT. June 13-16, 2015.

2.) *Chief Guest. Farewell and Welcome Reception Program for School Leaving Certificate Graduates*. Man Singh Dharma Higher Secondary School. Kathmandu, Nepal. July 3, 2015.

3.) *Participant*. ESRI Education GIS Conference. San Diego, California. July 18-24, 2015.

4.) *Understanding green waste management in Fresno, California*. International Conference on Waste Management & Environment. University of Malaya, Kuala Lumpur, Malaysia. August 20-22, 2015.

Difficulties Encountered

Two massive earthquakes of April 25 and May 12, 2015 and frequent aftershocks thereafter in Nepal have damaged many of the infrastructures of TU, including laboratories and thus limited Dr. Dangi's extended stay or second travel there. Sadly, Dr. Dangi's father, Mr. Lok B. Dangi, who was suffering from chronic liver disease and end-stage renal disease passed away on February 26, 2016 in Clovis, CA and this has left unrepairable loss in Dr. Dangi's life; thus, directly impacting his activities during latter half of his sabbatical leave.

Original Article

WM&R

Waste Management & Research
2017, Vol. 35(6) 618–626

DOI: 10.1177/0734242X17699683
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Assessment of environmental policy implementation in solid waste management in Kathmandu, Nepal

Mohan B Dangi, Erica Schoenberger and John J Boland

Abstract

In Nepal, full-fledged environmental legislation was rare before the democratic constitution of 1990. The first law covering the environment and sustainability was the Environment Protection Act 1997. While the Solid Waste Act was introduced in 1987, the problem of solid waste management still surfaces in Kathmandu. In order to understand the bedrock of this unrelenting failure in solid waste management, the manuscript digs deeper into policy implementation by dissecting solid waste rules, environmental legislations, relevant local laws, and solid waste management practices in Kathmandu, Nepal. A very rich field study that included surveys, interviews, site visits, and literature review provided the basis for the article. The study shows that volumes of new Nepalese rules are crafted without effective enforcement of their predecessors and there is a frequent power struggle between local government bodies and central authority in implementing the codes and allocating resources in solid waste management. The study concludes that Kathmandu does not require any new instrument to address solid waste problems; instead, it needs creation of local resources, execution of local codes, and commitment from central government to allow free exercise of these policies.

Keywords

Municipal solid waste, solid waste management, environmental policy analysis, solid waste legislation, Nepal, developing countries

Received 23rd December 2016, accepted 22nd February 2017 by Editor-in-Chief P Agamuthu.

Introduction

As low-income countries face ever increasing waste quantities, it is imperative that municipal solid waste (MSW) is handled appropriately to protect human health and the environment. A World Bank study revealed that urban residents worldwide generate nearly two times more solid waste (1.3 billion tonnes per annum) than they did 10 years ago (680 million tonnes per year) (Hoornweg and Bhada-Tata, 2012). While the amount of global solid waste generated will increase twofold by 2025, lower- and lower–middle-income countries will produce 53% of the increase. Countries in South Asia, where per capita waste generation varies between 0.12–5.1 kg day^{-1}, generate 70 million tonnes of solid waste annually (Hoornweg and Bhada-Tata, 2012).

The global cost of managing waste has gone up steadily. In 2010, it was US$205 billion and is projected to be US$375 billion by 2025. Developing countries will be hard hit by this increase in cost as they rapidly urbanise. Despite Kathmandu city's relatively modest MSW production of only 0.66 kg capita^{-1} day^{-1} (Dangi et al., 2011), chronic problems in waste management date back to 1970 (Dangi, 2009). Recent composition of household waste in Kathmandu consists of organic wastes (64.24%), plastics (15.96%), paper and paper products (8.66%), glass (3.75%), metals (1.72%), textiles (3.4%), rubber and leather (1.12%), and others (1.15%) (Asian Development Bank, 2013). Private companies and non-governmental organisations (NGOs) collect and transfer 30% of MSW (Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2007), informal scavenging handles 10% of solid waste management (SWM), and the formal recycling is still non-existent in Kathmandu.

Several reorganisation attempts have failed, resulting in reverting to riverbank disposal of waste. Mostly, MSW is still left uncollected in the streets of Kathmandu, even though it spends US$2.71 per capita per annum or 1.01% of its gross national product (GNP) on SWM. This amount is more than its peer cities in South Asia (Dangi, 2009) and what is recommended for cities of low- and middle-income countries (i.e. no more than 0.5% of their GNP on SWM) (World Bank, 1999). The average MSW collection efficiency in Nepal is 62% and the disposal rate is merely 37% (Asian Development Bank, 2013).

Efforts to organise SWM in Kathmandu have shifted from the municipal government in the earliest days of the city, to the national government to donor agencies, and back to municipalities after the termination of major foreign aid in the mid-1990s. Meanwhile, the laws governing SWM only serve the current political scenario, with new laws superseding the others over time

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and among different administrations. Table 1 lists the major solid waste-related laws enacted in Nepal before 2010 (His Majesty's Government of Nepal, 1997, 1999; Kanoon Kitab Byabastha Samiti, 2001; Ministry of Science and Technology, 2017; Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2004).

Dangi (2009) studied MSW issues in Kathmandu, Nepal, and examined the social–technical interface surrounding SWM comprising institutional, administrative, governmental, and technical processes. It was apparent, from that study, that the institutional component is a key factor required to sustain effective SWM. Also, the pattern of regulatory and structural adjustments in environmental legislation and policy is a concern in developing countries. Zurbrügg et al. (2012: 2126) argued that 'integrated and sustainable SWM should not only be given top priority, but must go beyond technical aspects to include various key elements of sustainability to ensure success of any solid waste project'. However, in Nepal, policymakers maintain their aspiration of sustainable SWM by continuously enlarging laws and codes while heavily emphasising the technologies used to transport and dispose of waste. These reforms have yielded no gains. Therefore, with respect to the organisational framework for SWM in Kathmandu from 1970–2010, this manuscript asks: *In what way do current institutional structures and practices contribute to the success or failure of policy in SWM in Kathmandu with a focus on government agencies.*

Table 1. Key solid waste-related regulations in Nepal before 2010.

Name of the legislation	Year enacted
Solid Waste (Management and Resource Mobilization) Act	1987
Labor Act	1991
Municipality Act	1992
Industrial Enterprise Act	1992
Environmental Policy and Action Plan	1993
Solid Waste Management National Policy	1996
Environment Protection Act and Rules	1997
Local Self-Governance Act	1999

Methods

At the time of this study, Nepal was in transition to a federal democratic republic and the current constitution was promulgated in September 2015. As the constitution is still in an early phase of implementation and the elections of the local bodies have not been held since 1997, the codes and laws governing SWM still follow an earlier order that was introduced by a strong unitary government.

The methods used included a field study conducted from June to August 2007 covering 336 Kathmandu city households using three stage-cluster sampling techniques. The households were selected from four strata; the strata, in turn, had been defined, revised, and validated in an earlier pilot study. The six city sectors identified in the pilot study of Kathmandu city were further tested using a percentage of poor building structures in each of the wards (Kathmandu Metropolitan City, 2005) and income to arrive with four new socioeconomic strata (lower-, lower middle-, higher middle-, and higher-income) for the field study as presented in Figure 1. Upon identification of wards, a focal point within the neighbourhood was determined, and a direction was randomly chosen, followed by selection of the first household positioned in that direction. The next household allotted in the study was the seventh household from across the street and the process continued until eight households were sampled in each of the 42 clusters with a total of 336 households representing 20 wards (Dangi, 2009). Survey respondents were all adults of at least 18 years of age. Given the cultural ties women and workers have in handling MSW at the household level, they were consulted where possible.

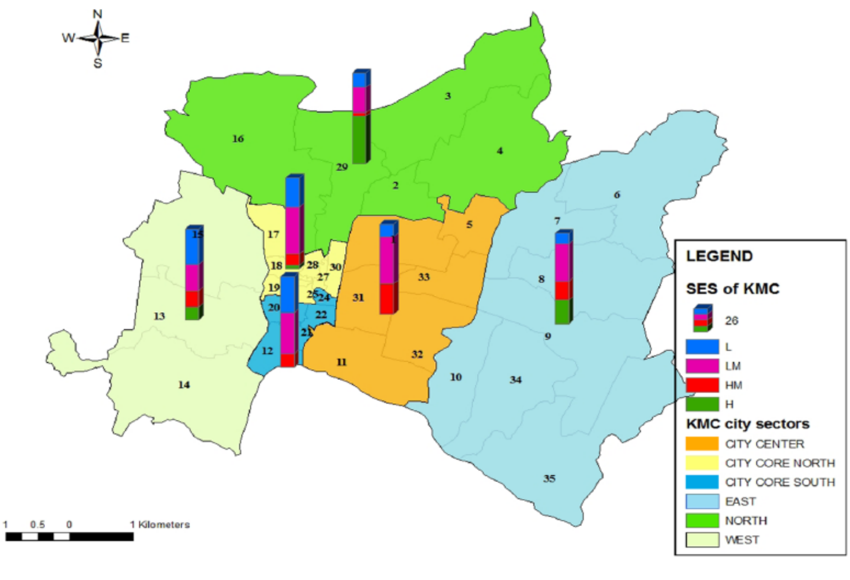

Figure 1. Socioeconomic stratification (SES) across Kathmandu Metropolitan City (KMC), where L, LM, HM, and H refer to lower-, lower middle-, higher middle-, and higher-income.

Table 2. Record of site visits to solid waste facilities for Kathmandu city.

Visit description	Location	Date
Gokarna Landfill	Gokarna	13 July 2007
Sisdol (active and proposed) Landfill sites	Sisdol area	14 July 2007
Evaluation of corridors along the Bagmati and Bishnumati rivers	Kathmandu	20 July 2007
Transfer station, streets, and *chowks*[a]	Kathmandu	July 2007
Waste disposal locations, containers, and dumps in wards and *toles*[b]	Kathmandu	January–February 2008

[a]*Chowk* = It refers to a common courtyard for houses that encircle it.
[b]*Tole* = A *tole* is known as a cluster of houses in a locality.

Dangi et al. (2008, 2009) describe the methods and findings of the pilot study, as carried out from 14–31 December 2005. While quantitative results from the field study are included in Dangi et al. (2011), the qualitative analysis utilised in this manuscript is more similar to that employed by Dangi et al. (2015). The key elements of the field study are described below.

Household survey

Questions pertaining to usefulness of environmental policies enacted were part of the household interview survey. The survey was conducted in a 10-day period, between 5–15 July 2007, by a group of 15 surveyors including the lead author.

Site observation

Table 2 provides a record of five visits to various present and past solid waste facilities for Kathmandu city. The visits were conducted by a Nepalese researcher accompanied by student assistants; the results were reported to the lead author in writing at the end of each visit. These observations were crucial to an understanding of how environmental guidelines, acts, legislations, and government programmes have functioned over time and the practice closely aligns with the definition of environmental policy analysis identified by McCormick (2001). They offered valuable first-hand information required to support the study's conclusions.

Individual interviews

A total of 38 structured interviews representing seven categories of individuals from different walks of life and having various levels of authority in organising SWM were conducted between July and August 2007 (Table 3). All of the interviews were performed by the first author and the responses were typed. In addition, the interviews were recorded using a Sony Cassette-Corder (TCM-200DV) and later analysed along with the typed script. The conversations were non-judgmental and were accomplished in a manner in which the respondents felt comfortable sharing their experience, knowledge, and traditions. Ability to converse fluently in the Nepali language and understanding of local traditions and social norms by the lead author helped to glean important decisions and efficacies of the laws.

Table 3. Categories of interviews conducted during July–August 2007.

Group type	Numbers
Kuchikars[a]	7
Kavadiwalas[b]	5
Private waste collectors and non-governmental organisations	7
Kathmandu city officials	9
Solid waste management officials	2
Foreign aid officials	3
Government ministers and secretaries	5
Total	38

[a]*Kuchikars* = Sweepers in the Nepali language.
[b]*Kavadiwalas* = Informal waste collectors or scavengers.

Group interviews

Group interviews were done at each of the landfill locations: Gokarna (closed), Sisdol (active), and the dumps along the river corridors in Sundarighat area. These interviews took place in July 2007. In every case, two student assistants presented questions to two or more villagers in more than one sitting to inquire about environmental compliance pursued by landfill development activities and post-closure cleanups undertaken.

Additionally, two visits to Sisdol took place in the summers of 2010 and 2013. The data collected was triangulated using existing literature.

Results and discussion

Solid waste legislation

Solid Waste (Management and Resource Mobilization) Act 1987. This act was created in 1987 to transfer the responsibilities of the Solid Waste Management Board to the Solid Waste Management and Resource Mobilization Center (SWMRMC) under the then Ministry of Works and Transport. (Recently SWMRMC has been renamed as Solid Waste Management Technical Support Center.) This change was intended to strengthen the efforts of the German Technical and Financial Aid Organization (GTZ), which was providing technical and financial assistance to Nepal in the area of SWM (Dangi, 2009). The act was amended in 1992 and 1997.

Despite the impressive set of duties that this act outlined, it never went into effect completely. Unlike what was stated in the act, the sale of compost ceased in 1990, and biogas was not generated from wastes until recent small-scale efforts. SWMRMC kept the city clean when the GTZ aid was available, but those efforts were primarily applied to major roads, intersections, and wealthier neighbourhoods. Fines ranging from Nepalese Rupee (NR)1000 to 3000 were set for violating the act, and inspection officers were appointed (Kanoon Kitab Byabastha Samiti, 2001). However, neither inspections nor collections of fines took place for long. Tuladhar (1996) notes that the revenue-generating activities, such as the sale of compost, sweeping charges, disposal fees, and collection of fines, were considerably reduced after the 1991 general election. He reported that the SWMRMC's yearly income in 1988/1989 and 1989/1990 rose by 94.5% and 184.7%, correspondingly, and for the 2 years after this period it declined by 8.4% and 4.4%.

The 1987 act was created with support from the German government and it became obsolete with the end of the project in 1993. In spite of being the first solid waste law in Nepal, it failed to provide effective legislation.

Solid Waste Management National Policy 1996. The Nepalese government adopted the Solid Waste Management National Policy in 1996. This policy required every local body, especially municipalities, to create a separate unit dealing with sanitation that included SWM. Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd (2005) determined that only Kathmandu city and 15 municipalities have standalone sections covering sanitation or SWM. The rest of the municipalities have combined public health and sanitation sections that deal with sweeping and hauling of wastes. The overall goal of making SWM orderly and effective by creating a centrally recognised body to facilitate the efforts of municipalities has drawn a lot of criticism. Thapa and Devkota (1999) argued that the creation of a new national agency, as envisaged in the SWM National Policy 1996, would produce an array of problems in managing local resources to handle SWM and would ultimately work against efforts to establish self-governance and promote the centralisation of resources. The GTZ proposed two options to Kathmandu Valley municipalities before the termination of its aid in 1993: Municipalities could sweep and collect waste or adopt SWMRMC and reimburse SWMRMC for the costs of sweeping and collection. At the same time, the national government had just introduced the Environmental Policy and Action Plan 1993 to allow wards to collect waste and deposit it in designated areas for municipalities to gather and landfill. In parallel, the government formed the Kathmandu Valley Development Council, which consisted of 39 ministers and secretaries, but only three representatives from local government. This initiative ignored the move to decentralise and assigned SWM responsibility to the Ministry of Local Development (MLD) (Tuladhar, 1996). (The MLD is now known as Ministry of Federal Affairs and Local Development.) When the GTZ left, its recommendations remained unfulfilled. Hard pressed to manage waste in Kathmandu, the government tried one measure after another without fully executing the previous policy.

In recognising the urgent need to organise SWM in Kathmandu, the government in 1996 commissioned a Fact Finding Mission from the GTZ to examine SWM in Nepal, and again the results suggested a need for a new national policy with comprehensive, integrated, clear, specific, and realistic objectives tied to the existing laws that deal with SWM (GTZ, 1996). Though this report suggested creating a holistic national policy accommodating previous waste laws, its timing and influence on SWM National Policy hint at an international partner's possible interest to revive its previous initiatives, i.e. SWMRMC. Tuladhar (2003, 1996) also reached similar conclusions. Joshi (personal communication, 21 July 2007) and Thapaliya (personal communication, 21 July 2007) added that the hasty preparation of this policy, while earlier policies remained unimplemented, suggests that the central government wants to stake a share of the income and political clout that international aid money SWM brings by having agencies like SWMRMC command the efforts at the national level. Also, it is believed that the government introduced a new policy as a backdoor effort to rescue SWMRMC at a time when SWMRMC was near bankrupt and burdened with 900 *kuchikars* (sweepers) drawing a salary equivalent to industrial workers. This was verified upon conversing with two former deputy mayors and Kathmandu city officials who reported that NR140 million was spent to retire these *kuchikars* from SWMRMC (Joshi, personal communication, 21 July 2007; Mainali, personal communication, 17 July 2007; Manandhar, personal communication, 24 July 2007; Thapaliya, personal communication, 21 July 2007). However, the major tasks outlined to create integrated plans for SWM, as stated in the policy objectives, were not pursued (UNEP et al., 2001). There was no provision in the budget to fund these tasks, nor was there any formal plan for doing so.

National Environmental Impact Assessment (NEIA) Guidelines for SWM Projects for Municipalities of Nepal 2005. Following the Environment Protection Act 1997 (EPA), SWMRMC published the NEIA in 2005. The guidelines provide instructions for Nepalese municipalities to develop initial environmental examinations (IEEs) and environmental impact assessments (EIAs) prior to the start of any SWM projects (ERMC et al., 2005). Though the guidelines are in place, Kathmandu city has not completely implemented them in SWM projects. In an inquiry to find out the exact nature of the IEE and EIA conducted for the Gokarna Landfill Site (GLS) and Sisdol Landfill Site (SLS), the former General Manager of SWMRMC, who was also a technical staff member for the construction of the GLS, stated that he lacked the necessary academic training to conduct these examinations and assessments. As a result, a Japanese expert was consulted for the technical study of the GLS (Shakya, personal communication, 18 July 2007). SWMRMC prepared the draft EIA for the SLS in 2001 and the Japan International Cooperation Agency (JICA) later verified it using its own environmental guidelines (Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2004). Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd (2004) described that the development of this landfill and site preparation were continuing while the EIA procedure was not completed. Note that the EPA does not permit development of a landfill without completion of the proposal by the authority and line agency (Sijapati, 2003). Also, the EIA information derived from the JICA study states that the water from Kolpu *Khola* (river) situated next to the SLS in the south is used for irrigation purposes only (Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2004). This contradicts the findings of the present research. In a group interview with local villagers in Sisdol, 10 of 40 respondents said that, in addition to irrigation, they still use the water for bathing; six said the water is used by cattle; five for human consumption; four for washing purposes; and three for other uses (see Figure 2.)

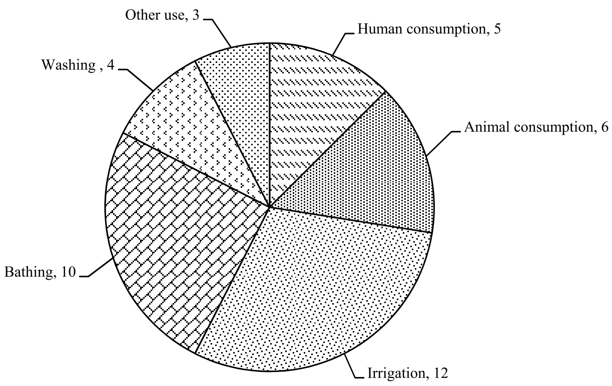

Figure 2. Response of Sisdol residents about the use of water from Kolpu *Khola*.

The EIA for the SLS also states that leachate generation would be managed easily by the Nepalese team and this would be ensured through frequent monitoring of water quality and the groundwater source near the SLS. In contrast to this statement, the leachate production has not been adequately managed. Interviews and records indicate that leachate is often discharged directly into the Kolpu *Khola*. Haphazard release of raw leachate into Kolpu *Khola* was also witnessed during the 2010 and 2013 visits (see Figure 3). The study found that the groundwater-monitoring probe had not been utilised for a long time and the leachate was poured directly into the Kolpu *Khola* despite the filtration system installed in the SLS. Shakya (personal communication, 18 July 2007) agreed that the leachate had been produced in the SLS, the flow of groundwater in the area is proportionately higher than estimated in the EIA, and the water quality had not been examined regularly. At the start of the GLS, there were no environmental laws requiring EIA in Nepal, but the mistake of ignoring the environmental impacts of landfill operations was repeated at the SLS despite the laws that were in place, including NEIA guidelines, during the construction of the SLS. NEIA guidelines were drafted in 2004 and the SLS came into operation on 5 June 2005. For other municipalities to apply an NEIA, it is imperative that the municipalities enhance their technical capacity before they can truly conduct any environmental studies. So, the NEIA unaccompanied by the professional capacity of individual municipalities to carry out the guidelines cannot lead to any improvement in the environmental impacts of SWM projects.

The procedure to create the NEIA guidelines was irregular. The participation in the preparation and finalisation of the guidelines was extremely limited. The consultations during the preparation of the guidelines did not include the far-flung municipalities or emerging townships and lacked wider public hearings and contribution. At the finalisation seminar, only two out of 54 participants came from outside of Kathmandu Valley, and the seminar lacked representation from other ministries or the large pool of

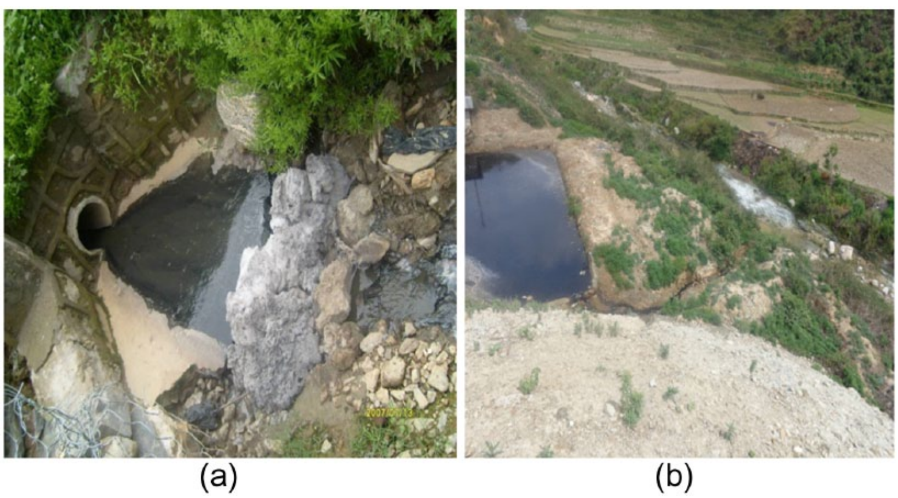

Figure 3. Direct discharge of leachate from the SLS into Kolpu *Khola* in (a) July 2007 and (b) May 2013.
(Photo credit: First author.)

international agencies. The only experts involved in the task were a SWM consultant and a mentor, who also served as a team leader. The lack of participation from experts in varied fields led to an absence of key issues of greater concern from the social, political, and environmental spectrum in the SWM projects identified in the document's objectives. Also, the guideline does not address speeding up the process for EIAs via local authority. Instead, all IEEs and EIAs must arrive at the MLD through the SWMRMC. Then EIAs must be approved by the Ministry of Environment, Science and Technology and IEEs by the MLD. This practice for EIA approval has hindered completion of permanent landfill.

Thus far, only three municipalities in Nepal have some sort of landfill in place and five others are still working on 'terms of reference' for landfill arrangements with the MLD (Gautam, personal communication, 22 July 2007). The poor level of performance at the Nepalese municipalities points to the low level of preparation and the incapacity of the SWMRMC to truly implement the NEIA guidelines.

Environmental acts

Environmental Policy and Action Plan 1993. The wards in Kathmandu generally lack the resources needed to provide sufficient formal collection centres. This leaves them unable to accomplish the tasks outlined by the Environmental Policy and Action Plan 1993, under which wards were required to collect waste and deliver it to a central collection point so that the municipality could then collect and process the waste for appropriate disposal. When interviewed, two former Kathmandu city ward chairmen stated that this policy had not been executed because dumpsters were not available in many of the wards for waste disposal; and wards that had containers either had too few containers or they were not emptied often enough, leaving mountains of wastes near them (Dangol, personal communication, 18 July 2007; G Joshi, personal communication, 16 July 2007). Also, Upreti (personal communication, 17 July 2007) mentioned that either the containers were very tall (~4 feet) forcing children and workers to deposit wastes outside of the containers and thus creating unhygienic environments in *toles* (neighbourhoods), or the closest container was far away (~3 km), making it difficult for people to carry wastes to the containers. He added that because of a lack of space to locate a container within the hamlet of a ward and the filth it had created around the few containers they had, the general public urged Kathmandu city to do away with the containers.

In a survey question designed to gauge the perception of the assistance provided by ward offices for the SWM options practised in wards or *toles* as a result of this policy, 95% of the respondents said that they had not received any support from ward offices, while 5% responded that they have received support, such as compost bins and waste buckets. It indicates a low level of effort by wards to put this policy into practice.

Environment Protection Act 1996 and Environment Protection Rules 1997. The Ministry of Population and Environment (MOPE) was created in September 1995, followed by the Environment Protection Act 1996 and the Environment Protection Rules 1997 (Ministry of Population and Environment, 2000). Together, these two laws are known as EPA 1997. This legislation emerged as a key step forward in balancing economic development with a fragile environment in Nepal. Passed by the Parliament in 1997, this law is regarded as a major achievement of the environmental movement in South Asia (Sijapati, 2003). It is the first comprehensive law protecting the environment and the development and management of biodiversity. As such, it addresses an omission in the Constitution of Nepal 1990 by defining pollution measures and suggesting mitigation options more systematically. Some of the objectives of this law are to find balance between economic development and preservation of the environment, protect environmental health and public safety by reducing the harmful effects of development, and promote the wise use of natural resources to avoid any further deterioration of the surroundings.

The act can be critiqued as ambiguous owing to only general mentions of accurate accounts of pollution measures and discussions of environmental issues (Sijapati, 2003). The act requires the assignment of environmental inspectors, but this has not taken place. There is no independent agency charged with enforcement of this directive of the act, nor has the government spelled out the quality, qualifications, tenures, and agreements for assigning inspectors to maintain the act. There was supposed to be an Environment Protection Council at the MOPE comprised of various political parties and experts to furnish policy feedback to the government, but progress was delayed until 2000, and when it was formed it became a useless entity because other powerful ministries often obscured its role (Ministry of Population and Environment, 2000; Sijapati, 2003). Sijapati (2003) further adds that the execution of the act is difficult as it emphasises only monetary fines without due consideration of other options, including imprisonment, market measures, and tax breaks.

After much anticipation, the EPA was enacted as umbrella legislation in pursuit of environmental preservation and conservation endeavours mentioned in the 1990 Constitution of Nepal. While the legislation is a milestone achievement in the volumes of Nepali laws, its ineffectiveness has many impacts in sector-wide development, including SWM. Chief among its flaws, the law lacks enforcement and standards. Enforcement of the EPA 1997 is delayed because of lack of standards to measure the pollution level, government ministries creating laws and regulations on an ad-hoc basis that frequently contradict each other, the absence of mechanisms to periodically evaluate the performance and effectiveness of laws and to monitor outcomes, government agencies implementing the laws without cooperation among themselves or with private partners, and a command and control approach in adopting legislation by the government. By the mid-1990s, Nepal already had 69 different acts covering broad environmental issues and it was a party to 17 international treaties (UNESCAP, 1997). However, government agencies do not monitor these instruments, there are no resources in local government to do so, and any instruments put in place are very deficient.

Kathmandu city did not have any record of fines collected and rules administered, including the EPA. Instead, the municipality reported that after the political transformation of 2006, Kathmandu has been unable to implement any local rules for SWM (Shrestha and Rai, personal communication, 22 July 2007). It was found that Kathmandu city's 10 to 12 code enforcers are not enough to monitor the population of 800,000 (Manandhar, personal communication, 24 July 2007). According to senior managers at Kathmandu city, the laws to manage MSW exist, but the provisions for enforcement have not been arranged by the government ministries, and without those provisions municipalities are not able to prosecute violators (Thapaliya, personal communication, 21 July 2007). This reinforces the argument that the command and control arrangement in Nepal embraces laws, but the government agencies that are supposed to implement the laws are not empowered to do so, and in the end many of the laws are not implemented. Not only is there a lack of EPA mandated inspectors at the national level, but MOPE, the agency that was supposed to arrange the inspectors, was disbanded in 2005. In the vacuum, it is not surprising that environmental legislation appears ineffective and meaningless in Nepal.

Even after the EPA was in place, Kathmandu city continued to actively landfill along the banks of the Bagmati and Bishnumati rivers, in addition to using GLS and SLS. The landfilling practice at these sites exceeded the benchmark set by this act for an EIA, and hence they should have been closed and rehabilitated with post-closure care. If any, the only rehabilitation occurring is the building of roads on the top of compacted waste lining some stretches of the river. More needs to be done to address the leachate that is seeping into rivers, the haphazard practice by local residents of trapping landfill gas for cooking, and the slums that are developing on the landfill area along the river corridors.

Although the activities in Sisdol had started after the EPA was passed, the development of this area was moving forward without a complete EIA. The necessary steps of the EIA do not seem to be followed in the river corridors. For example, a former Minister of the MLD said that 300 families in the Sundarighat area along the Bagmati River were each receiving NR 3000 per month from Kathmandu city in return for letting the city dispose of wastes in the slum areas (Pandey, personal communication, 19 July 2007). This was confirmed during a group interview in the squatter area on 20 July 2007. The slum dwellers accused the city government of bribing the well-off and elites in Sundarighat while leaving the poor with putrid garbage next to their abodes.

Other laws

Municipality Act 1992. One of the goals of this act was to make cities accountable for wastes piled in streets, lanes, and footpaths and enforce their collection and proper disposal (Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2004). The act states that local entities can generate earnings from the sale of wastes and carcasses. It gives municipalities authority to collect up to 50% of roof-top tax from parties that have profited from SWM-related businesses and municipal governments can charge a 1% *octroi* tax for goods entering the municipality (Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2005). The *octroi* tax was repealed in 1999 and it was replaced with local development fees based upon the amount of the *octroi* tax that was collected in 1997/1998. This move has created more reliance on the central government. Former elected officials describe that a decrease in the steady source of local income has seriously affected local activities, including SWM. Shrestha (2001) reported that the *octroi* tax used to contribute 90% of total income of a municipality and Kathmandu city had contracted the collection of the tax for NR 700 million per annum. In 2004/2005, local development fees in Kathmandu accounted for 61% of its total tax revenue, however, this was to be completely discontinued by the end of 2013.

Other revenue-generating opportunities have been lost because of the sale of wastes and carcasses has not been institutionalised and different authorities collect the scrap tax. Although the Municipality Act permits cities to sell wastes, the districts in the Kathmandu Valley are allowed to collect scrap tax from the sale of waste under different acts (Bhattarai, 2003; Thapa and Devkota, 1999). The districts call for tender for scrap materials with a pre-identified tax rate for the valley. Whoever quotes the larger amount wins the tender, and the revenue is shared equally among the three districts. The contractor pays a 10% value added tax to the revenue department and this is passed on to exporters. None of this revenue from the districts trickles down to the municipality for SWM.

Local Self-Governance Act 1999 (LSGA). The LSGA states that waste disposal, cleanliness, and sanitation are the duties of local ward committees; and municipal governments are responsible for the collection, transportation, and ultimate deposition of wastes. It allows municipalities to collect waste disposal fees from people and impose fines of up to NR 15,000 for not disposing of wastes in designated locations. Despite the directive to collect fees for SWM, Kathmandu city has not implemented this provision except in the households where there is voluntary door-to-door collection of wastes in place (Bhattarai, 2003). Given the inability to expand the revenue base locally and incapability to enforce codes as mentioned earlier, municipalities also seem responsible for the failed policies.

Answers to some survey questions in this study also point to the failure of the LSGA. A question about the use of selected locations for throwing solid waste in the streets found that 34% of survey participants thought that people could get away with throwing waste in the streets, thus suggesting a practice of illegal disposal in the streets. Another survey question that sought information about the changes in SWM in *toles* found that many people (49%) believed that the amount of MSW has increased and a little over 9% replied that MSW has increased but the workforce remains the same. This information supports the need for more local human resources to manage the increased quantity of MSW and the fact that those resources have not been put in place bolsters the view that LSGA fails to fulfil its SWM mission in Kathmandu.

In section 234 of the LSGA, it states that the central government can provide supervision, monitoring, and direction required to maintain the local environment (Sijapati, 2003), which may work against its own spirit. In Nepal, decentralisation may have only acted as a *mantra* for every regime, administration, and political party, but it has never been reality in any substantial way (Pandey, 1999). Experts believe that the devolution of authority in this law is only limited in theory and to turn this statute into a powerful tool, it must encourage participation from grassroots. Also, with the co-existence of the SWM National Policy with various past SWM-related legislations that have neither been amended nor annulled presents severe difficulties in exercising LSGA (Nippon Koei Co Ltd and Yachiyo Engineering Co Ltd, 2005).

Bryld (2003) explains that municipalities in Nepal have weak arrangements for SWM, possess inadequate sanitation, unclean abattoirs, and public machineries that still need adequacy as attempted by the LSGA. Officials in Kathmandu city reported that the fines for SWM lawbreakers, as stipulated by the LSGA, are difficult to impose in the prevailing political instability (Shrestha and Rai, personal communication, 22 July 2007). Despite the code (Figure 4), people still strew litter in the streets and are contributing to unhygienic SWM practices on the part of the local community, one more factor leading to the failure of environmental policies. Although they penalised wrongdoers until 2006, the difficulty arises when Kathmandu city cannot put them in jail or take stricter actions. The Chief Executive Officer of the city echoed those statements, saying, "'LSGA provides provision for fines, but not a single law in the country spells out how it will punish the offenders' (Thapaliya, personal communication, 21 July 2007).

Figure 4. Display of a posted street sign to discourage street littering near Basantpur in Kathmandu by a local club. (Unofficial translation: Notice: 'Clean your *tole* by yourself'. It is requested not to dispose garbage in this location. Violators will be fined between NR 500 to 15,000.)
Photo credit: Timothy Barrett.

Conclusions

While efforts to organise SWM in Kathmandu have shifted from the municipal government in the earliest days of the city, to the national government, to donor agencies, and back to municipalities after the termination of major foreign aid in the mid-1990s, the laws governing SWM continue to serve the existing political scenario with one superseding the others with the passage of time and changes in administrations. While the SWM Act 1987 was thought to be very comprehensive in its early days, later governments added the Municipality Act 1992, Environmental Policy and Action Plan 1993, and SWM National Policy 1996. An umbrella act on the environment, i.e. the EPA 1997, was an outgrowth of the democratic constitution of the 1990s. These laws, as well as the results of the Fact Finding Mission and the continued presence of SWMRMC, have led to the belief that the volumes of SWM laws that overlap and contradict each other while encouraging management from the central government, block any attempts at successful SWM efforts. The LSGA 1999 touts the *mantra* of self-governance while SWMRMC does not assist deficient municipalities in creating it and instead exerts its position to claim a piece of the waste management endeavour. Government agencies develop law after law and almost every project and task is plastered with codes, but the national government does not provide sufficient tools and agencies lack the background and implementation capacity to successfully handle waste. Most laws are so poorly implemented and so rarely enforced that there is no chance to evaluate them over time.

Municipalities and local entities need the authority to craft their own projects and engage in creating resources with some help from the central government and aid agencies. Realising *kuchikars'* and *kavadiwalas'* deeply rooted cultural, emotional, traditional, and social attachment in SWM in Kathmandu (Dangi, 2009), the importance the informal sector plays in undertaking urban environmental issues in developing countries (Dangi et al., 2009; Wilson et al., 2006), and flourishing private sectors and NGOs, any new environmental policies and laws should consider augmenting the delicate balance via revision and amendments of acts instead of complete overhaul and deletion of old codes.

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Impacts of environmental change on agroecosystems and livelihoods in Annapurna Conservation Area, Nepal

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A R T I C L E I N F O

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Mustang
Myagdi

A B S T R A C T

To understand local perceptions of the impacts of environmental change in two mountain districts of Nepal — Myagdi and Mustang — between 2010 and 2014, a survey, focus groups, town hall meetings, and extensive consultation with local stakeholders were conducted, supplemented by analyses of soil, rainfall, and temperature data. Mountain people in Nepal shared their perceptions of environmental change in their everyday lives, including agricultural practices and tourism activities. While ordinary individuals welcome the construction of new roads, elites still prefer to maintain trails and the status quo. People are concerned about the introduction of mosquitoes, increases in insect pests and plant pathogens, and other vectors along with roads. Snowfall has decreased and rainfall has been unpredictable. Mean minimum winter temperatures have increased and the mountains are experiencing shorter winters and less snow accumulation, which threaten the livelihoods of people that depend on fresh water. While people with means are replacing their traditional homes with modern homes, that is beyond reach for average Mustangi citizens. Expansion and diversification of agriculture, adoption of sound soil management techniques in Marpha village of Mustang and Shikha village of Myagdi, and growing forest cover in Shikha are some indicators of enhanced community managed practices. The coping strategies and indigenous practices adopted by local people in the region against hardship and environmental changes could serve as examples in similar mountain settings elsewhere.

1. Introduction

To some, Nepal is considered a living laboratory with its varied cultural practices and diversity of flora and fauna, made possible by the various microclimates that prevail in a small region of the country. The area, in less than 200 km, extends northwest from southeastern Nepal with an elevation of 60 m in Kechna Kalan to the Himalayas adjoining the Tibetan Plateau, with elevations over 8800 m. The geomorphology of Nepal includes three distinct regions: The Northern Region has 38% of the landmass and is dominated by the Himalayan Range with elevations of 5880–8848 m; the Central Region (36%, 1830–5880 m) is populated by river basins, mountain valleys, and Mahabharata Range; and the Southern Region (26%, 60–1830 m) consists of Siwalik Range, Chure hills, and

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inner *Tarai* (plains) (Shankar, 1999). Ninety percent of the precipitation in Nepal occurs during the summer monsoon (June to September), followed by a dry winter season. The average annual precipitation is 1516 mm with minimum of 210 mm in Mustang and maximum of 5460 mm in Pokhara region. The temperature in *Tarai* ranges from 4 to 44 °C, whereas in the Himalayas subzero temperatures are very common during the winter months (Shankar, 1999). Nepal is also rich in water resources with seven important river basins, including the three major ones — Karnali in the west, Sapta Koshi in the east, and Narayani in the center. Among the tributaries of Narayani, Kali Gandaki River, originating in Mustang Bhot *Himal* (mountain), is very important because of its year-round flow and the landscape around it.

The Kali Gandaki River carries large quantities of glacial deposits with high bed load yielding a black river, and forms the deepest gorges in the world, providing immense hydropower potential. Because it flows through central Nepal, the river is a cultural and geographical dividing line between the eastern and western Himalayas. To document indigenous practices and traditions in combating impacts of environmental change in Nepal, two different districts of Nepal were studied from either side of the Himalayas: Myagdi and Mustang.

Mustang is the least accessible district among the seventy-five districts of Nepal and 77% of the people there are involved in agriculture (National Trust for Nature Conservation (NTNC), 2008). Likewise, the economy of Myagdi is largely dominated by agriculture. Tourism is equally popular in both places because of the famous Annapurna Circuit trek that passes through them.

Textures of soils at the Mustang study sites were loam, silt loam, silty clay loam, sandy clay loam, and clay with most texture (58.9%) belonging to silty loam (Shrestha et al., 2017). Soil textures found in Myagdi are similar to its neighboring district of Prabat where most soils were silty loam (Khadka, 2012).

The importance of social, cultural, economic, spiritual, and moral aspects of a society in understanding the impacts of climate change on local people was discussed by Byg and Salick (2009) in the Eastern Himalayas. Byg and Salick (2009:165) also identified, "…models and other scientific instruments are not sufficient to understand or tackle complex problems such as climate change." Additionally, researchers found people's observations are deeply rooted in local traditional values and physical settings but are rarely documented in scientific literature even though they can inform global level processes and vice versa (Berkes et al., 2001; Laidler, 2006; van Aalst et al., 2008; Wilbanks and Kates, 1999).

The climate is changing in Nepal with greater intensity and impact on higher altitudes, such as in the Trans-Himalaya (Becken et al., 2013; Shrestha et al., 1999). The Tibetan Plateau is experiencing some of the highest rates of warming on the planet (Liu and Chen, 2000). Extreme weather events and unpredictable precipitation trends have been projected for the region (Nyaupane and Chhetri, 2009). People in the Lower Mustang Valley have witnessed shifting weather patterns, such as warming winters that have lengthened the growing season and extended it northward to the highlands.

While the demand for energy in the developed world will increase by 19% in the next two decades, the demand for energy will rise by 84% in developing countries by 2050 and 56% of this demand from developing countries will be attributed to India and China alone (Kitchen, 2014). Surrounded by China to the north and India in the other three directions and home to eight of the fourteen tallest peaks that are 8000 m in height or above, Nepal will likely feel the impact of the mounting energy demand and the effects of the associated greenhouse gases. Globally, the earth is warming and the first ten years of this century have been the hottest decade in history. Within the 100-year period from 1906 to 2005, the planet warmed by 0.74 °C and the rate of warming of the earth in the last 50 years has been 1.3 °C, double the rate of the whole century (Dessler, 2012).

The Himalaya is the source of fresh water for more than a billion people and 5–10% of the world's cereal crops depend upon it. Most of the currently accessible ice and snow supplying fresh water to the region will disappear in summer months by 2050 (Kitchen, 2014). Many Himalayan glaciers are losing ice more quickly than they can be replenished. Water shortages during summer months will impact irrigation and drinking water supplies. Forest fires may erupt in the dry season compelling people to migrate and tensions could rise in the region. Flooding and landslides in the rainy season may deteriorate people's quality of life. IPCC (2007) projects similar life-threatening forecasts for many parts of Asia, including a greater risk of diarrheal and infectious diseases, large-scale storms, typhoons, sea level rise, flooding and inundation, glacial snowmelt, extreme water events, collapse of sandy beaches, unusually high fire risks, and frequent landslides.

In parts of the mountain region of Nepal, very little is known about the factors driving environmental change there, how people are coping with the changes, what resources are in place to tackle them, and in what way people from various walks of life are impacted (Gentle and Maraseni, 2012). Accounts of local and traditional knowledge in climate change and its impacts have been greatly overlooked by many contemporary studies (Byg and Salick, 2009). Implementation of climate change policy has been rather slow in Nepal because of its formal and rigid bureaucratic process that doesn't prioritize adaptation activities (Chaudhury et al., 2016). In addition, the Local Adaptation Plan for Action instituted in 2011 in Nepal to incorporate climate adaptation in development planning and initiate climate resistant growth has encountered major hurdles, including ignorance of climate change, resource exploitation, and lack of political backing (Baral, 2013; Government of Nepal (GON), 2011).

To understand some of this gap, this paper utilized field-based methods and studied variables responsible for altering traditions and living conditions in Annapurna Conservation Area (ACA), Nepal. The ACA is the largest protected area of Nepal covering 7629 km^2 from 1000 to 8091 m in altitude in five of the 75 districts of Nepal and includes 57 village development committees with rich biological and cultural diversity (NTNC, 2009). The ACA is a model illustration of park-people cooperation in the conservation of natural resources, biodiversity, sustainable development, ecotourism, women's involvement in conservation, use of renewable energy sources, protection of cultural heritage, and community-based resources management. However, it faces challenges from the more than 100,000 people of various indigenous communities that inhabit the area (Bajracharya, 2012). To examine this topic more rigorously, we located study sites along the famous Annapurna trekking routes, including Shikha village in Myagdi and the towns of Lete, Marpha, Jomsom, and Kagbeni in Mustang (Fig. 1). Shikha is the southernmost study location. Jomsom and the other Mustangi

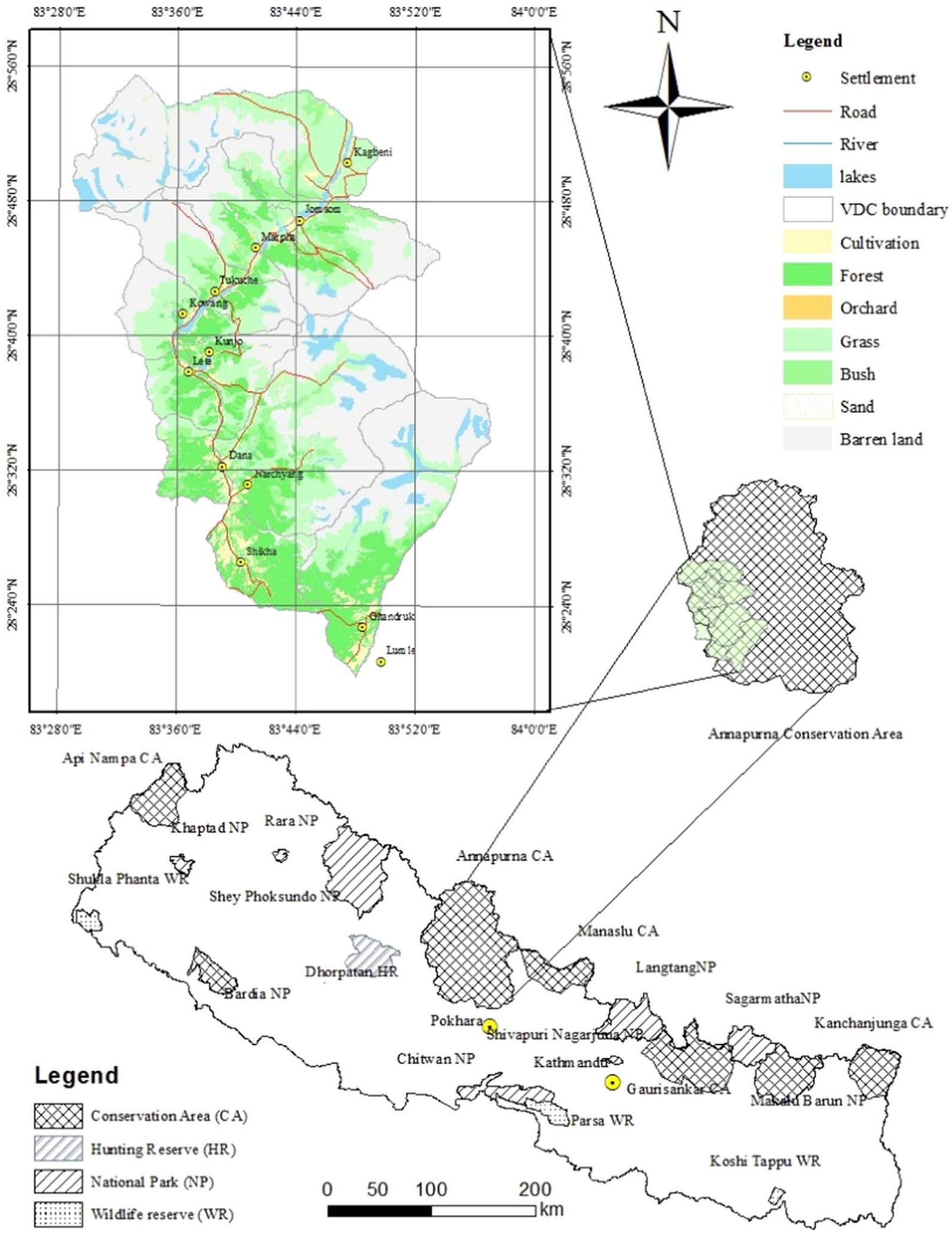

Fig. 1. Map of Annapurna Conservation Area, including research sites.

towns are close to the north edge of the study area.

The objective of this study is to understand local peoples' perceptions of the impacts of environmental change in Myagdi and Mustang between 2010 and 2014 and to determine if traditional practices are helping to cope with environmental challenges faced by local residents.

2. Theoretical approach

This study focuses on people's perception of climate change based on their local experience and the everyday lives of individual farmers, hoteliers, entrepreneurs, community leaders, policymakers, conservation officers, and government staff in the study area. Aligning with the research approach taken by Becken et al. (2013) of "practical wisdom," the two Nepali researchers and the corresponding author of this manuscript have spent several weeks in multiple years in the study locations since 2010 conversing with and learning from seasonal farm workers, community leaders, trekkers, school teachers, and conservation officers and interacting with elders about their traditional belief systems and connecting the dots to understand local environmental conditions and attitudes.

While studies from the Arctic regions have provided valuable information on the local variations in climate change and its impacts (Fox, 2002; Kofinas, 2002), involving indigenous people and their experience can enhance what can be learned from global climate models and measurements (Byg and Salick, 2009). By bringing not only the local experience, but seasoned local experts that speak the language, share the traditions, believe in similar value systems, and can easily relate to the people from study locations (unlike similar studies that were carried out by expatriates or foreign researchers), this research adds more substance to the understanding of "social ecological systems" where issues from time-space geography intermix (Berkes, 2002; Holling, 2001).

The firsthand account of the impact of global changes in the study locations noted by Aase et al. (2009) and Chaudhary et al. (2007) were also relevant for the research. Various studies have applied social science perspectives in understanding environmental change utilizing viewpoints both regional and global to pin down the drivers of change. Aase et al. (2009), Becken et al. (2013), Chaudhary et al. (2007), and Nyaupane and Chhetri (2009) helped in authenticating the techniques and methods used in the research and offered systems approach needed to investigate problems that overlap in more than one traditional discipline and demand metadata analysis.

Because Jodha (1992) argued that inaccessibility, fragility, marginality, diversity, niche, and human adaptations are part of specificities distinguishing mountains from *Tarai* or lowlands, this research followed the unique characteristics that the study locations present in terms of remoteness, sensitivities, isolation, range of existing meteorological and cultural variation, the distinctiveness mountains offer, and people's ability to cope with a changing environment. Therefore, it's useful to understand and acknowledge the importance of different environmental factors and their impact on climate change in the region. While Sharma (2000) and Nepal and Chipeniuk (2005) studied the peculiarities of the mountain after Jodha (1992) in tourism development, Nyaupane and Chhetri (2009) claim that there is a need to elucidate the effect of climate change in the tourism and recreational sector. As people along the ACA trails heavily depend upon the flow of tourism, we anticipate that identifying the parameters that affect environmental change in the area will help fill some of this void.

3. Methods

The remoteness of Shikha and Marpha presented more difficulties in accessing the study sites. Preliminary investigations in both of the localities were performed in the summer of 2010 and follow up studies were conducted in the summers of 2011 and 2014. A detailed breakdown of qualitative, quantitative, and field-based methods adopted in the study is presented in the subsections below.

3.1. Preliminary study

The researchers first visited Myagdi and Mustang districts from July 11 to 18, 2010. This part of the study was crucial to understanding the gravity of the problem and for framing the research methods. During the visit, personal contacts were established along the Annapurna trekking route with Annapurna Conservation Area Project (ACAP) staff in its branch office in Shikha and local villagers, entrepreneurs, and leaders in Marpha and Jomsom. To get a better sense of the environmental challenges faced by locals in Mustang, it was important to interact with people from different community sizes, livelihoods, and distances from trekking routes. Thus, 10 households from Kagbeni (a smaller settlement), 33 households from Marpha (a medium settlement), and 40 households from Jomsom (a larger settlement) were surveyed on July 15, 16, and 17, 2010, respectively. There were 22 structured questions in the survey covering demographics, precipitation, agricultural practices, water and wastewater, energy, and solid waste topics. We implemented the questionnaire first in Kagbeni, then in the larger villages of Marpha and Jomsom. All three surveys began selecting households from the central point of the villages in four directions (East, South, West, and North) until the required number of households were met using cluster sampling techniques followed by systematic sampling (Dangi et al., 2011, 2015).

To understand the perceived impact of environmental change from different viewpoints, individuals with experience varying from a layman to a former assistant minister were interviewed using open-ended questions and a bottom-up approach (Table 1).

Table 1
Description of interviews conducted in study sites during 2010–11.

Individual/Groups	Title	Date	Numbers
Siddhartha B. Bajracharya	Executive Officer, NTNC	August 15, 2011	1
Kshetra Gurung	Officer, ACAP Branch Office, Shikha	July 13, 2010	1
Bhakti Hirachan	Former *Mukhiya* (headman), Marpha	July 16, 2010	1
Gajendra Hirachan	Hotelier, Hotel Majesty, Jomsom	July 17, 2010	1
Nar B. Hirachan and villagers	Former Assistant Minister of GON, Marpha	August 8, 2011	41
Shikha High School teachers and villagers	Shikha High School, Shikha	August 7, 2011	15
Chandra B. Thakali	Retired Civil Servant, Jomsom	July 17, 2010	1
Three elderlies (without names)	Retired Jomsom residents	July 17, 2010	3
Total			64

3.2. Field study

The field study conducted from August 4 to 16, 2011 afforded an opportunity to expand the findings of the preliminary study and identify the existing indigenous knowledge base used to preserve fragile environments in the mountainous region. Having gained firsthand accounts of difficulties local residents confronted along the Annapurna trekking route, we narrowed down the problems into three thematic areas: soil, water, and forest. Linking the problems with appropriate resource persons covering three of the five key national environmental problems of Nepal (water, soil, forest, solid waste, and air) may help address these issues.

During the visit, a survey of 16 households each was conducted in Shikha on August 6 and Lete on August 8. There were 33 structured questions in the survey arranged by topics including demographics, water, soil, ecosystem services, and other question types, employing the aforementioned cluster and systematic sampling design. Additional interviews conducted in 2011 were also listed in Table 1 above. Altogether 64 people were interviewed.

Moreover, to uncover any associated effects that agroecosystem and livelihood have had in natural resources, soil samples were collected from Shikha and Marpha. Six soil samples from each settlement were collected and analyzed. At each village, three of the samples were obtained from cultivated soil and three obtained from uncultivated soil. A 50 m transect was established at each collection site and samples were collected at 15 m intervals along the transect using a trowel to a depth of 15 cm. Soil organic matter (SOM; Walkley and Black (1934)), nitrate nitrogen (NO_3-N), and ammonia nitrogen (NH_3-N) were quantified in the soil samples. Soil organic carbon (SOC) content was calculated from the SOM data. Soil samples were carried in Ziploc bags from the field collection sites to the laboratory, dried for storage, and were then analyzed.

3.3. Focus group discussion and consultations

An extensive follow-up study of Shikha, Marpha, and Jomsom occurred from May 22 to 30, 2014. An interaction between villagers and the research group was organized at the ACAP building in Shikha on the evening of May 24, where local people shared their perceptions of climate change, and the researchers had the opportunity to ask questions. The interaction was well attended by elderly citizens, including mothers' groups. Also, treating the ACAP office as a central point of the settlement, earlier in the day on May 24, twelve focus group discussions were conducted with three households in each of the four directions. Based on the outcome of the field study in Shikha and to construct a collaborative knowledge, a set of three questions were asked in each of the focus group discussions, which lasted about 45 min.

On May 26, researchers interacted with Marpha residents in a town hall meeting attended by many current and former leaders, farmers, and schoolchildren as well as *mukhiyas*, mothers' groups, and Marpha Foundation (an organization working in the area). On the morning of May 27, the research group observed agricultural fields, learned how practices are shifting toward cash crops, inquired about the use of organic manure, and visited waste burning sites. The conversations with locals provided information related to soil quality, water quality, and air pollution. During the afternoon, an ACAP staff member from its Unit Conservation Office in Jomsom presented information regarding ACAP's conservation work to the research group and responded to queries. A separate consultation was held with district level officials, providing information on governmental efforts in soil management, climate change, erosion control, and riverbank management.

Each of the surveys and focus group discussions began after receiving oral consent from the participants to protect their privacy.

Moreover, temperature and rainfall data for Jomsom (study site), Lumle (near Shikha), and from a nearby urban settlement (Pokhara) were obtained from the Department of Hydrology and Meteorology (DHM, 2016, 2014).

4. Results and discussion

4.1. Factors affecting environmental change

While both Mustang and Myagdi met or exceeded the human development index (HDI) of 0.49 for Nepal in 2014, their adult literacy rates are an indication of their remoteness in relation to Kathmandu (Table 2). Despite being the second least populated district of Nepal with the total population of 13,799 (CBS, 2011), Mustang barely produces enough grain to support its population six months out of the year and the area has persistent poverty where 55.5% and 19.8% of the households are ultra-poor and poor, respectively, with a poverty deprivation index of 33 (NTNC, 2008). Even with their respective locations along the trekking route, a large majority of residents in Marpha and Jomsom were engaged in agro-pastoral activities (Fig. 2). As stated earlier, the district wide

Table 2
Human development report of Mustang and Myagdi districts of Nepal (UNDP, 2014).

Index	Mustang	Myagdi	Kathmandu	Nepal
Population	13,452	113,641	1,744,240	26,494,504
Life expectancy (yr)	65.04	70.05	68.55	68.80
Adult literacy (%)	61.35	65.16	84.04	59.57
Per capita income (PPP $)[a]	1922	1028	2764	1160
HDI	0.508	0.490	0.632	0.490

[a] PPP = purchasing power parity.

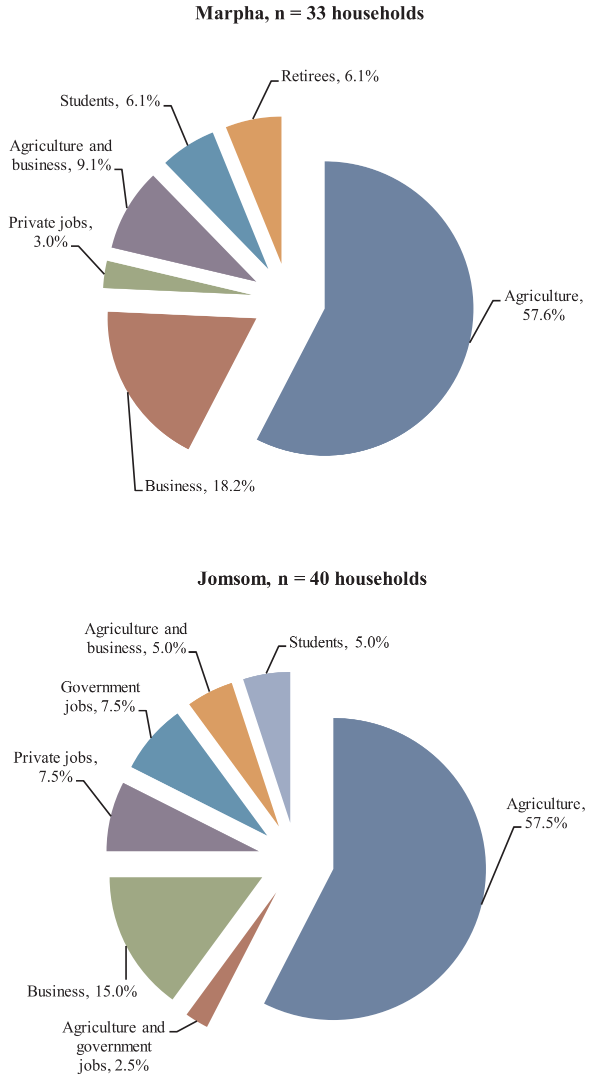

Fig. 2. Respondents' profession in Marpha and Jomsom.

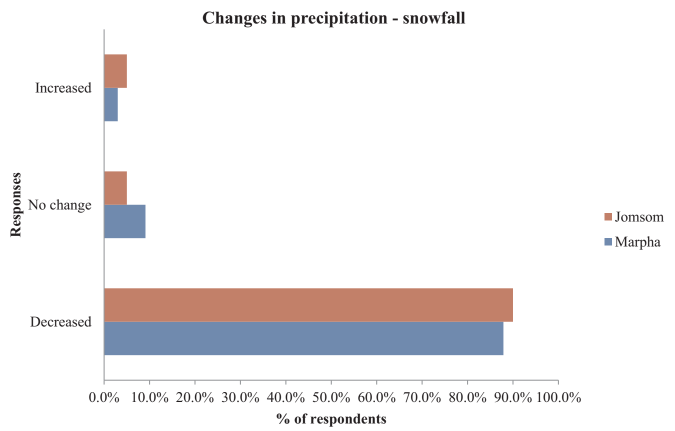

Fig. 3. Changes in precipitation pattern – snowfall.

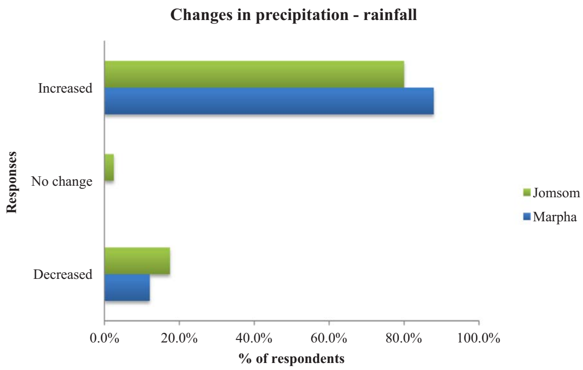

Fig. 4. Changes in precipitation pattern – rainfall.

average for involvement in the agricultural profession was about 77% (NTNC, 2008). Most respondents in both places were involved in agriculture; people occupied in business were the second largest group in Marpha and Jomsom. Jomsom is the seat of Mustang district, so some of the participants had government jobs. Businesses were represented by hotels, most often run by local Thakali people. Shops primarily consisted of gift stores operated by Tibetan migrants in the main business districts and tourism trails in Marpha and Jomsom. Because of the importance of a good snowpack to farming, domestic water supply, and ecotourism, a survey question was asked to elicit information on factors affecting crop production. In Marpha, 87.9% of the respondents (90% in Jomsom) indicated that snowfall has gone down and the same percentage of respondents (80% in Jomsom) believed rainfall has been more intense thus affecting crop yield (Figs. 3 and 4.)

The precipitation clock seems to be changing over time. For instance, Jomsom received an intense snowfall early in the month of *Kartik* (October-November) in 2007 (G. Hirachan, personal communication, July 17, 2010). An 82-year-old man mentioned he hadn't seen this in *Kartik* for long time. A nearly one-foot-deep snowfall took a huge toll on apple trees because of the excessive weight of the snow on juvenile leaves. A Jomsom native and retired civil servant also talked about soil erosion, increases in insect pests and plant pathogens, random precipitation, and depletion of drinking water aquifers resulting from diminishing snowfall and deforestation, and recalled that early snowfall in the month of *Kartik* was normal in Jomsom some forty years ago (C.B. Thakali, personal communication, July 17, 2010). In fact, the weather in 2007 was very strange in Nepal as Kathmandu received its first snowfall in 63 years on February 14, 2007 (Reuters, 2007).

Additionally, 90.9% of the survey participants in Marpha stated the temperature has increased and 87.5% mentioned the same in Jomsom. The most recent data from DHM (2016) concur that the mean maximum and minimum temperatures of Jomsom have indeed changed. The mean maximum and minimum temperatures were 18.66 °C and 5.4 °C in 1965, 18.44 °C and 5.72 °C in 2010 (at the time of the survey), and 17.77 °C and 9.93 °C in 2014 (during the follow up visit), respectively. The temperature readings are from Jomsom Airport located between the towns of Jomsom and Marpha and could represent both. It is apparent that the mean maxima have trended to the lower side, and the mean minima have clearly increased, thus supporting the findings of the survey. Another reason for public perception could be higher summer temperatures, for example in July 2010 while the survey was being conducted the mean maximum and minimum for Jomsom were 22.2 °C and 13.8 °C, respectively. People are also concerned about the changes, as three elderly Jomsom residents stated on July 17, 2010: "Now, winters are warmer and summers are colder. Our cropping pattern has shifted from naked barley (white), mustard, buckwheat, and wheat to tomatoes, eggplant, corn, and chilies." Both Chaudhary et al. (2007) and Dahal (2006) have recounted experiences by farmers in Mustang and its neighboring district, Manang, where they can now grow cauliflower, cabbage, chili, tomatoes, and cucumber without greenhouses.

Local people in Kagbeni reported on July 15, 2010 their perception that snowfall has declined in last 20–25 years from about half a meter to 10 cm; rainfall has decreased; the monsoon is delayed; crop production has dropped; floods are less frequent; Kag *Khola* (river), a tributary of Kali Gandaki River has become narrower and deeper making it difficult for people to cross; the flow in Kali Gandaki is shrinking; retreating groundwater has impacted the drinking water source; and irrigation, mosquito infestations, and fuelwood collection have gotten worse. People spend a whole day fetching firewood that lasts them merely a week. With the weakening precipitation in Kagbeni, crop yield for potatoes, wheat, and buckwheat has declined. Similar observations were shared by an hotelier in Jomsom who described that agriculture had been severely impacted because of emigration of youth from the area, which has left 50% of the land uncultivated.

The impact of environmental change has been more deeply felt in parts of the study locations. Eighty one percent of respondents from Shikha, and 75% in Lete, indicated that they had often experienced drought and/or floods in recent years. Evidence of a higher level of impact in Shikha was echoed by people in the neighborhood of Khopra Danda on July 13, 2010, who described that those engaged in sheep farming were no longer active because of prolonged drought and decreasing amounts of herbaceous grasses.

An insufficient water supply was a chronic problem in Shikha and Lete with a number of households stressing that either there was not enough water to begin with or it was a problem many months out of a year. The perception of reduced water supply was further corroborated by responses to whether there had been any changes in the rainfall pattern in the last few years or not, where 50% of the Shikha respondents answered yes with sometimes (Lete, 25%), 43.8% replied yes with usually (Lete, 56.3%), and 6.3% replied no (Lete, 18.8%).

Consultation with district level officials in Jomsom on May 27, 2014 identified shifting apple farming to the north due to the warmer climate, emerging pests and diseases such as apple scabies, damage of crops by armyworms, rising number of landslides, and increases in soil erosion and sediment load in the riverbed as key challenges for Mustang. While the increase in sediment load in the riverbed could make irrigation more difficult, Gauchan (2010) and Suryananshi (2016) reported that the prevalence of new diseases and a decrease in yield are the reasons why apple farming is moving to colder regions in the north. Similarly, Rai et al. (2015) concluded that the lack of cool weather has a direct bearing on apple production. Among the positive impacts of climate change reported by the officials were expanding apple farming to the north, longer vegetable growing season due to warmer temperatures, and shortened harvesting period. Adverse impacts of climate change described were less and erratic rainfall, diminishing snowfall, recent flooding, and shrinking drinking water supply.

Shrestha et al. (1999) project that dry seasons will become drier in the driest region in Nepal. Decrease in snowpack and deforestation has already impacted drinking water supplies in Marpha; people now have to rely on *Muhans* (sources of water) remotely located at higher elevations. With a greater evaporation rate and reduced snowpack in the mountains, the surface water flow in Kali Gandaki River could be impacted and this will have an immediate bearing on water sports and tourism (Nyaupane and Chhetri, 2009). Shrestha et al. (1999) showed a greater level of warming is taking place in the mid-mountains and Himalayan region than in the lowlands and *Tarai* and this could directly influence the river water flow. While Gentle and Maraseni (2012) stated that mountains are warming faster than global averages within last 100 years, Shrestha et al. (1999) established that in Nepal the Middle Mountain and the Himalayas have experienced temperature increases ranging from 0.06 to 0.12 °C per annum after 1977. Fujita et al. (1997) and Kadota and Ageta (1992) obtained similar results regarding diminishing snow cover and glacier extent in the Himalaya. Since the Himalayas are the source of fresh water and food for 1.3 billion people across South and East Asia (Kitchen, 2014), changes in snowpack will alter the livelihoods of people in the region. The ND-GAIN Index (2015) also placed Nepal as 55th most vulnerable and 70th least ready country among the 182 nations measured in six life-supporting categories – water, food, ecosystem service, health, human habitat, and infrastructure. Because Nepal has lost 6% of its glaciated area from 1970 to 2000 and 25% of glacial cover in northwestern China could be depleted by 2050, the 3 °C rise in temperature by 2100 projected by climate models could be disastrous for many people in this part of the world.

Forty years of rainfall data reveal Jomsom, in the Trans-Himalaya, receives the least precipitation, while Lumle and Pokhara both get much more rainfall than Jomsom (DHM, 2014). A ten-year average of precipitation patterns in these locations provides evidence that annual rainfall has decreased in all three places during 2003–12 compared to the previous decade (Table 3). Winter precipitation has gone down in Lumle and Pokhara in comparison to 1973–82 and 1983–92, whereas it has increased in Jomsom. The pre-monsoon rainfall has generally decreased in Lumle and Pokhara and has increased in Jomsom. The monsoons have become more intense in Jomsom and Lumle, while Pokhara has experienced a decrease in rainfall during 2003–12 compared to previous decades.

Shrestha et al. (1999) established a small but distinct increase in maximum annual temperatures in the Himalaya. A 32-year temperature data set obtained from DHM (2016) indicated mean maximum and minimum temperatures of Jomsom, Lumle, and

Table 3
Precipitation pattern (mm) in the last forty years in and near study locations of Jomsom, Lumle, and Pokhara.

Precipitation pattern	Location	Year			
		1973–82	1983–92	1993–02	2003–12
Annual (Jan-Dec)	Jomsom	251.59	214.7	286.25	280.4
	Lumle	4993.64	5345.33	5785.4	5436.4
	Pokhara	4026.43	3716.51	4362.87	3599.31
Winter (Dec-Feb)	Jomsom	18.62	17.83	37.78	24.71
	Lumle	87.85	115.07	106.72	87.67
	Pokhara	78.33	90.49	73.3	66.52
Pre-monsoon (March-May)	Jomsom	52.28	55.11	65.99	62.01
	Lumle	459.55	438.72	563.41	450.77
	Pokhara	562	442.32	646.37	521.94
Monsoon (June-Sep)	Jomsom	143.62	101.7	150.15	169.07
	Lumle	4205.79	4578.21	4865.44	4676.55
	Pokhara	3135.94	3044.51	3463.88	2830.02
Post-Monsoon (Oct-Nov)	Jomsom	37.07	40.06	32.33	24.61
	Lumle	240.45	213.33	249.83	221.41
	Pokhara	250.16	139.19	179.32	180.83

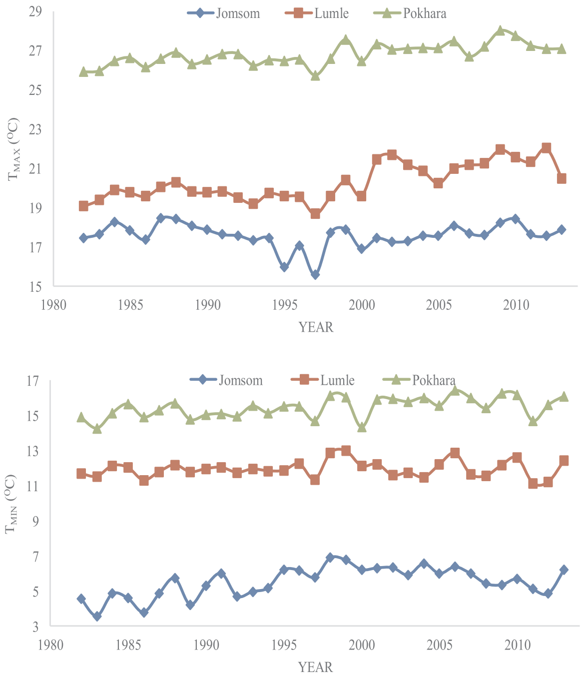

Fig. 5. Variation in mean annual maximum and minimum temperatures of the three locations.

Pokhara have climbed between 1982 and 2013 (Fig. 5). There is a clear trend that temperatures in the region are warming with the mean minimum temperature of Jomsom increasing by 1.64 °C in 32-year period, the most of the settlements, and Lumle's mean maximum temperature has warmed by 1.38 °C in the same period. These findings in Lumle (mountainous region) and Jomsom in the High Himalayas are consistent with the conclusions in Shrestha et al. (1999) that the mountains in Nepal are getting hotter and the first dozen years of this century have been the warmest on record since 1850 (Kitchen, 2014). The measured values for temperature (Fig. 5) and precipitation (Table 3) are consistent with our survey results.

There clearly are huge geographic differences in rain abundance across the Himalaya. Pokhara and Lumle have, respectively, 13 and 19 times as much rain as does Jomsom (Table 3). Obtaining similar time-trends from a larger number of locations (geographically dispersed) is essential for elucidation of any temporal patterns.

Climate change is global; responses are local. This is the conclusion reached by Becken et al. (2013) and Byg and Salick (2009) in studies of cultural responses to climate change in Nepal and Tibet, respectively. Rainfall is highly variable depending on geography, directions of locally prevailing winds, and the presence of topographic features that can induce locally wet or dry regions. Thus, temporal patterns may differ across geographically distinct regions in Nepal, adding greater urgency to obtaining temporal data from a large number of locations as suggested above.

Rainfall patterns are locally more highly variable due to topography and wind patterns than are temperatures. Therefore, regional trends in rainfall in the Himalayas will need to be done on a more geographically localized scale than was possible for the air temperature study of Shrestha et al. (1999). Becken et al. (2013) and Byg and Salick (2009) showed responses to climate changes are themselves highly localized and culturally mediated. To predict the effects of climate change on people's lives (as it pertains to

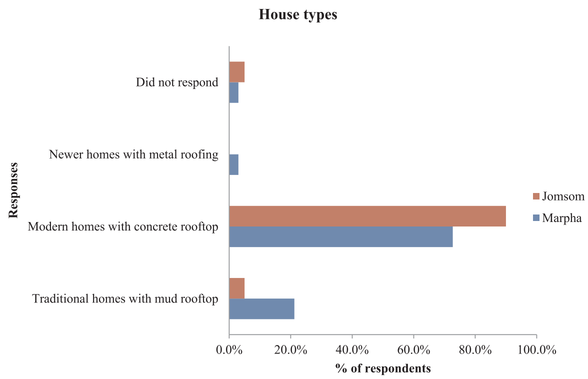

Fig. 6. House types in Marpha and Jomsom.

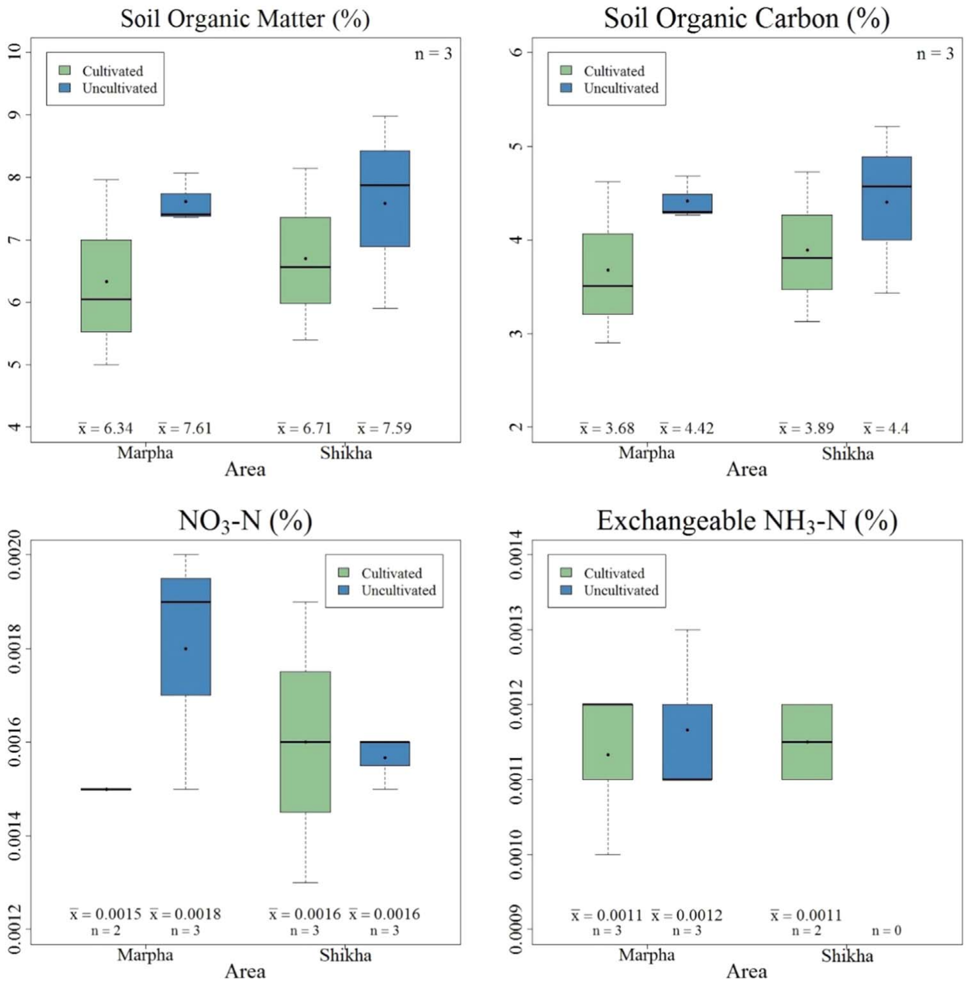

Fig. 7. Boxplots of soil variables from Marpha and Shikha.

rainfall), temporal and location trend data will be needed from a large number of locations, with attention to local geographies. At this point, it is not clear whether such data exists for Nepal, but pursuing such data and trend analyses could be important future work.

4.2. Effects of economic development, construction and expansion of roads, and tourism activities on livelihood

Research showed house types found in Marpha and Jomsom have changed from those that were traditional in the areas. Most homes in Marpha and Jomsom are now modern homes with concrete rooftops (Fig. 6). Nyaupane and Chhetri (2009) also concur that winter snowfall has lessened and spring rainfall has increased thus creating stagnant water on the flat rooftops of old-style homes made with mud and clay and erosion of structures, and this has noticeably affected motels and teahouses. Similarly, Dahal (2006) mentioned that unpredictable monsoons, diminishing winter snow, post-winter and unusually heavy precipitation in the summer months, and windier river valleys are causing roof leaks and wall damage to traditional mud-roofed homes.

On the other hand, there are good reasons to continue traditional farming techniques. In Marpha, 60.6% of the respondents and 50% in Jomsom perceived that crop yields have declined. Analyses of the soils of Marpha and Shikha indicated that cultivation resulted in significant losses of SOC. This is not surprising, as cultivation of topsoil has consistently been found to reduce SOC by studies around the globe. SOM consists of 58% SOC, so having both values go down with cultivation is expected. This is an important loss because approximately 95% of the nutrients in most soils are contained in the SOM. Lab results also indicate no statistically significant differences in the mean values of inorganic nitrogen, NO_3-N, NH_3-N, and between cultivated and uncultivated soils at both Marpha and Shikha (Fig. 7). This inorganic nitrogen represents the nitrogen available for plant uptake. Organic nitrogen in the SOM is usually the largest pool of nitrogen in most soils, so the differences in SOM between cultivated and uncultivated soil represent important disparities in soil nitrogen content as well as other nutrients including phosphorus, sulfur, and micronutrients. Although this data indicates there is some loss of soil quality as a result of cultivation due to loss of SOC, the cultivated soil still has a relatively high SOM and SOC content, suggesting the traditional agricultural practices used by farmers in Shikha and Marpha are sound and

Table 4
Yearly flow of tourists (in numbers) from Birethanti Check Post[a] (ACAP, 2013).

Year	Entry	Exit
2008	26,458	31,430
2009	29,269	34,174
2010	31,734	37,917
2011	38,054	40,526

[a] Birethanti is one of the entering check posts for foreign visitors arriving into the ACA located southwest of Lumle in Fig. 1.

should be continued.

Many residents still use fuelwood for cooking in both Marpha and Jomsom although liquefied petroleum gas (LPG) has been introduced in the area with the recent development of roads. From our survey, 90.9% of the households in Marpha (92.5% in Jomsom) obtain their energy from fuelwood. The collection of fuelwood from local forests has led to massive deforestation in the region.

Public needs such as availability of goods and services, healthcare, access to market, and organized distribution of drinking water are more directly available for individuals residing in or near towns located along the trekking route. All of the survey participants in Marpha and Jomsom stated that their drinking water comes from community taps, and 97% of the respondents in Marpha (100% in Jomsom) indicated their wastewater is discharged into a canal, which then goes to agricultural fields or drains into the Kali Gandaki River. A majority of respondents (93.8% in Shikha and 81.3% in Lete) stated they receive their drinking water from a tap and the same percentage in Shikha (93.8% in Lete) mentioned the taps are located within 0–30 min' walk from homes.

Road construction between Jomsom and Lo Manthang has impacted tourism in upper Mustang, where ~ 23 km of the construction was not finished and if completed, would destroy tourism (G. Hirachan, personal communication, July 17, 2010). The same observation was true for Jomsom as the flow of foreign visitors had drastically reduced. Moreover, an Executive Officer of NTNC, remarked, "We have not been able to address road issues. Money allocated for EIA [Environmental Impact Assessment] later went to Engineering of [Nepal] Army." (S.B. Bajracharya, personal communication, August 15, 2011). NTNC (2008) reported road construction did not follow any of Nepal's existing environmental policies and the impacts include decrease in prices of essential household merchandise, business with Tibet, human trafficking, smuggling, and generation of solid waste. Now, solid waste is a growing environmental concern in both Marpha and Jomsom, where it is primarily burned in a simple grate furnace after some sort of collection and very little segregation. In addition, the consequences of not following environmental policies consist of frequent landslides, road closures, destruction of trails causing loss of revenue from trekkers, and air pollution.

The flow of tourists in the ACA has steadily increased (Table 4). In all of the four years examined, ACA exit numbers are greater than entry numbers, so exit numbers were used as a basis for comparison. When the flow was further broken down by months, it was found that in 2010 the exit number of 719 tourists for the month of July was the lowest. Historically, the two monsoonal months of June and July attract the fewest visitors. The finding aligns with the claim of G. Hirachan (personal communication, July 17, 2010) that the flow of foreign visitors had dropped at the time of preliminary study. NTNC (2009) also confirmed that the number of people visiting the ACA peaked in 2000 with 73,407 visitors, then fell, and regained numbers in 2008 with 72,175 visitors. The total annual numbers reflect the flow of visitors from all of the ACA entry points including individuals arriving via airplane in Jomsom.

In Shikha, 18.8% of the survey respondents blamed forest destruction/degradation on anthropogenic activities and 6.3% on those and other factors. The corresponding values in Lete were 43.8% and 18.8%. The larger number of participants in Shikha choosing not applicable (68.8%) than in Lete (31.3%) hinted that the forest cover in Shikha was healthy and still thriving deep into the ACA territory. This was also similar to the point that people in Swata made during the 2011 field study. (Swata is an adjoining village of Shikha to the northeast direction.) Being inaccessible with a direct all-season road, transporting chemical fertilizers could be very costly to the region; therefore, many people used organic manure that seemed to have helped the growth of forests and agricultural crops. It was more evident in Shikha because of the abundance of vegetation and crops that exist throughout the village. In an inquiry into the practices employed to enhance soil fertility in Shikha, 75% of the participants mentioned they used organic fertilizers, and 62.5% stated they did the same in Lete. Soil loss was still a problem in both places as a combined 81.3% of the respondents in Shikha and 75% in Lete answered yes with usually and yes with sometimes, in that order, to the survey question on this topic.

Focus groups yielded important information on public viewpoints about local environmental challenges and the ways the problems have accelerated within the last five years, as mentioned in Section 3.3 (Table 5). Fifty-nine individuals took part in 12 focus group discussions; the responses included votes for positive and negative outcomes from road construction, effect of climate change in agroecosystem, and dependency on the forest. Among the positive results concerning roads, transportation and healthcare and living standards each received the most votes at ten and increases in local tourism and property value both garnered only one vote. Within the negative results concerning roads, erosion and landslide was voted for most frequently at nine and impact of roads on price of goods, no change in property value, road accidents, higher expenses, lower income, and loss of biodiversity each got the lowest vote at one. Tomatoes and bitter gourd can be grown had the greatest focus group support at three regarding the positive results of impact of climate change in agroecosystem. Cold and less snowy winters; decrease in crop yield; drought, black snow, and hail; and rainfall pattern and intensity each scored the most support of focus group discussions for negative results of climate change in agroecosystem at ten, nine, eight, and seven, respectively. For people's dependency on the forest, the most positive votes were for

Table 5
Public responses of focus group discussion in Shikha on May 24, 2014. The numbers inside the parentheses indicate the number of times the response has been stated.

Questions	Positive results	Negative results
What changes have you observed after the construction of a new road in Shikha in the last five years?	Transportation (10) Market for local products (5) Higher price for potatoes (2) Healthcare and living standard (10) Cheaper goods (2) Employment (2) Increase in local tourism Exposure and opportunities (2) Population retention and new settlement (2) Increase in property value	Insecurity and cultural influence (3) Decrease in foreign tourism (4) Erosion and landslide (9) Deforestation and degradation (4) Pollution (2) Impact of roads on price of goods No change in property value Road accidents Higher expenses Lower income Depletion of agricultural land (2) Loss of biodiversity
How has agroecosystem production been altered because of climate change such as rise in temperature, variation in rainfall, and snow within the last five years?	Increase in crop production (2) Start of tunnel farming Initiation of mushroom plantation Tomatoes and bitter gourd can be grown (3) Opening of fisheries Introduction of cauliflowers and new beans	Decrease in crop yield (9) Disease in potatoes (3) Prolonged harvesting period Rainfall pattern and intensity (7) Severe weather and temp. (3) Cold and less snowy winter (10) Change in crop calendar (3) Shift in rhododendron flowering Drought, black snow, and hails (8) Pollution and mosquitoes (2)
In what ways has your dependency on the local forest changed within the last five years?	Less dependent (5) Growth of protected forest cover (3) Increase in private forest (4) Rise in use of wild vegetables	Requirement of permits (6) Curbed grazing and grass buy (4) Reduction in livestock (2) Restricted access to forests (7) Shortcoming in medicinal herbs Continued use of firewood Adoption of fossil fuels (5) Destruction of crops by monkeys

less dependent at five and the most negative votes were for restricted access to forest at seven.

Participants in Shikha on May 24, 2014, mentioned that roads ease access to transportation, reduce deforestation by making LPG available, bring markets closer to them, shorten the distance to hospitals or ambulatory care services, enhance the ability of elders to go to district headquarters to collect pensions, reduce dependence on firewood, help boost community forests and comprehensive management of natural resources, and allow people to market their grass along with firewood and fodder. The negative impacts described included degradation of forests during road construction, felling of trees, soil erosion and frequency of landslides, dust, use of roads limited to summer, loss of agricultural land, air pollution, cultural influence by outsiders, and a decline in tourism as travelers prefer to use traditional trekking routes. Also, community members gathered at the town hall meeting in Marpha on May 26, 2014 stated that apple and potato production have remarkably decreased and increases in insect pests and plant pathogens and climate change are compounding the problem.

4.3. Implications of traditional practices on environment

Traditional knowledge comprises the body of information, beliefs, rituals, innovations and practices of indigenous and local communities sustained and developed by native people, peasants, and communities in interactions with their biophysical environment (Berkes, 2004).

Such knowledge is embedded in social systems and coevolve with ecological processes (Gómez-Baggethun et al., 2013), can improve livelihoods (Chaudhary et al., 2007), sustain ecosystem services (Gadgil et al., 1993), and build resiliency in “social ecological systems” (Berkes and Davidson-Hunt, 2006). This type of traditional knowledge has generally been disseminated orally for generations worldwide and such practices are crucial for sustenance of environmental resources at the local level.

Moreover, the agro-pastoral system of the ACAP region is dependent on traditional agricultural practices and indigenous crop diversity. Conventionally managed agricultural productivity not only provides a major contribution to local consumption, but also substantially contributes to feeding the livestock in Manang and other parts of the ACAP region (Chaudhary et al., 2007). Animal husbandry is an integral part of the farming system; manure is an essential fertilizer (Aase et al., 2009). Like in other parts of ACAP, pine (*Pinus roxburghii*) needles in Shikha and juniper (*Juniperus communis, J. indica*) branches in Marpha are collected from the forest and used for animal bedding, which is then mixed with dung and urine and added to the manure heap.

Likewise, plants and plant products are the primary source of traditional medicine and nutritional requirements, and are highly valued resources in Nepal. Traditional medicine is the primary mode of healthcare for most of the population of ACAP, and local herbal practitioners called *Amchi* play an important role in healthcare and food security. There are more than 100 locally available plant species used to treat different ailments and diseases (Bhattarai et al., 2010). These are some of the few remaining areas among the remote and mountainous districts of Nepal where Tibetan medicinal practice remains in use.

Farmers in Marpha have explored an avenue to cultivate an important medicinal plant, *Anacyclus pyrethrum* (locally called *Akarkara*), along with the apple orchards as a source of household income. It is regularly used in *Ayurvedic*, Unani, and herbal medicine worldwide for treatment of men's diseases, common cold, toothache, and has libido stimulant and aphrodisiac properties.

It was also noticed that local people in Shikha and Marpha are dependent on wild edible plant species and gather substantial amounts of wild plants to meet their daily nutritional needs. Several species are also used for trade. These include some species of the onion family (*Allium carolinianum)*, arum family (*Arisaema flavum*), asparagus family **(***Asparagus filicinus)*, and nettle family **(***Urtica dioica)*. A few, including wild onions, have high trade values. However, the traditional knowledge of the use of wild food plants is decreasing with the introduction of modern packaged food items in Mustang and Manang as in many parts of the world (Bhattarai et al., 2009).

Traditional knowledge is a valuable heritage for the communities contributing in a complimentary way to managing the resources in the ACA. But, people have shown concern regarding the uncertain status of the indigenous knowledge that is being lost due to global changes.

5. Conclusions

This research highlighted people's perception of changes in precipitation, temperature, weather pattern, livelihoods, agriculture, and tourism and identified the importance of traditional knowledge. The study supported the argument that the mountains in Nepal are experiencing extreme weather events and villages in Myagdi and Mustang districts of Nepal are dealing with the impact of climate change. Nepal presents a unique opportunity to study the effects of climate change on everyday life. Even then, the information about how environmental factors affect livelihood and subsistence living is limited. For centuries, the mountains presented barriers to the flow of knowledge and communication among indigenous people in parts of the Nepalese Himalayas as well as isolating them from the contemporary society of Kathmandu and *Tarai*. More than 82% of people in Shikha (Myagdi) (CBS, 2014) are from Magar caste and 84% of people in Mustang are Gurungs and Thakalis (NTNC, 2008), which may explain differences in belief systems, traditions, practices, and eventual decision-making. While a section of the public led by elites and entrepreneurs still prefer limited construction of roads in the *Himal*, ordinary citizens seem to be thrilled with new roads, piped water, cooking gas, and electricity. While people seemed to be concerned about the outbreak of potato diseases, introduction of mosquitoes, deforestation, decrease in snowfall, inconsistent rainfall, leaks in roof-tops, northerly migration of apple farming, rise in temperature, droughts, and loss of tourism along the previously established trekking trails, their responses appear to be positive for shorter harvesting periods, longer growing seasons, expansion of forests in Shikha, accessibility to markets and healthcare facilities, and prolonged tourism activities during drier periods. A majority of people in Marpha and Jomsom are still engaged in agro-pastoral system despite being at the hub of the renowned ACA trail. Solid waste generated may have received some attention from the ACAP; the issues with water and wastewater still dominate in Marpha and Jomsom. Drought is an ongoing problem in both Shikha and Lete.

Traditional knowledge is being lost due to environmental and social changes. Presently people seem to be well informed about environmental changes; however, there is a disconnect between government authorities, policymakers, and experts in tackling the effects of changing weather on local livelihoods. The expansion of meteorological stations to gather time and place specific temperature and precipitation data and persistent engagement among the local people, scientific community, and government could help address some of the global issues these innocent mountain communities are facing in Nepal.

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