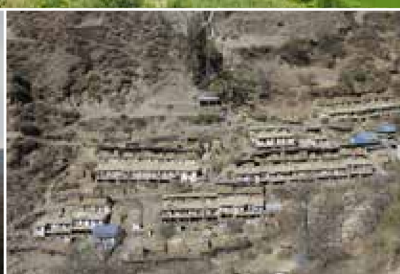
FOR MOUNTAINS AND PEOPLE

Workshop report

Joint BMUB-ICIMOD Expert Consultation Workshop on Hindu Kush Himalayan Mountain Soils

20–21 March 2018, Kathmandu, Nepal




About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalaya – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

ICIMOD gratefully acknowledges the support of its core donors: the Governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Sweden, and Switzerland.

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Contents

Acronyms and Abbreviations

BMUB	Germany's Bundesministerium fur Umwelt, Naturschutz, Bau und Reaktorsicherheit
CoCoFe	code of conduct for the management of fertilizers
FAO	Food and Agriculture Organisation of the United Nations
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GSP	Global Soil Partnership
HKH	Hindu Kush Himalaya
ISRIC	International Soil Reference and Information Centre
LDN	land degradation neutrality
MoFE	Ministry of Forest and Environment
NDCs	nationally determined contributions
SDGs	Sustainable Development Goals
SEALNET	South-East Asia Laboratory Network
SOC	Soil Organic Carbon
UNCCD	United Nations to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
VGSSSM	Voluntary Guidelines for Sustainable Soil Management

Background

Soil management and conservation are critical interventions for sustaining ecosystem services that are crucial for food and water security. They are integral to the delivery of multiple ecosystem services and, in this sense, pillars of wellbeing and co-existence. From the a Sustainable Development Goals (SDGs) perspective, they link to several targets. From a scientific perspective, there is increasing acknowledgement of the crucial role soil plays in ecosystem functioning (Adhikari and Hartemink, 2016). The multiple benefits produced from the soil are called soil functions (Blum, 2005).

The Hindu Kush Himalaya (HKH) is the youngest mountain range in the world. Its southern slopes are marked by fragile geology and high erosion rates, while in the Hindu Kush and Tibetan regions, the soil organic matter turnover and mineral mineralization rates are much slower.

While the HKH region has evolved into a landscape of striking beauty with unique and rich biodiversity, the setting also presents high stakes for the people who live here. The geographical factors of the HKH lead to low productivity across the region and difficult farming conditions. Soil information related to food security, water scarcity, climate change, biodiversity loss, and health threats is limited in this region. To address these challenges, the International Centre for Integrated Mountain Development (ICIMOD) teamed up with Germany's Bundesministerium fur Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) to organize an Expert Consultation Workshop on HKH Mountain Soils.

Sustainable Development Goals (SDGs) related to Soil Issues

SDG 1 on ending poverty in all its forms everywhere; inclusive agriculture, food production, and off-farm economies can create jobs and eliminate hunger

SDG 2 on Zero Hunger: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.

SDG 13 on Climate Action: Take urgent action to combat climate change and its impacts.

SDG 15 on Life on Land: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

Numerous factors contribute to declining soil fertility in the HKH—landslides, erosion, overgrazing, poor soil management practices, intensified droughts and rainfall, and unplanned urbanization and construction, among others. These factors pose serious challenges to food security and ecosystem sustainability in the HKH region (Adhikari and Hartemink, 2016). Also the conversion of forestland to other land uses in the HKH region is quite high, which results in a decline in soil nutrient content (Sharma, Rai, Sharma, and Sharma, 2004).

The organic carbon stored in soils is assumed to contain twice the amount stored in all terrestrial plants and more than three times that in the atmosphere. Carbon preservation and sequestration in soil thus offers an effective means for offsetting greenhouse gas emissions while also producing other benefits such as increased agricultural production and improved ecosystem services.

In the post-Paris Agreement phase, the scope of mitigation strategies has widened from an earlier focus on curbing fossil fuel emissions to acknowledging the ameliorative importance of soil carbon sequestration. Thus, soil interventions require a better understanding of the carbon cycle, how carbon is emitted from the soil, and how it can be sequestered through reversal processes. This knowledge is particularly lacking today in the HKH, where adverse impacts of climate change are felt more acutely at higher altitudes than in the lowlands.

Objective

The expert consultation, financially supported by BMUB, intended to bring together soil experts from the entire HKH region to forge a common pathway for securing soil functions in the mountains. Lessons from this consultation will be linked to ICIMOD's work on mitigation, mountain resilience, and adaptation to climate change. Furthermore, ICIMOD has seized the opportunity to develop its expertise on mountain soils, an issue that is becoming more relevant throughout ICIMOD's regional member countries.

The specific objectives of the consultation were:

- To assess the status of soils in the mountain regions of ICIMOD's eight regional member countries;
- To collect best practice examples for reversing land degradation and enhancing soil functions for improved ecosystem services;
- To highlight the role of soil conservation in mitigation and adaptation actions; and
- To demonstrate how soil conservation can lead to the fulfillment of national and global commitments and conventions (NDCs, UNCCD, UNFCCC, and SDGs 1, 2, 13 and 15).

Rationale

This consultative workshop was motivated to develop strategies with a set of action plans to move soil management and conservation from science to practice given that there was no work package specifically designed to deal with, and address the mountain soil issues. At the suggestion of BMUB, a need was felt to bring together experts from ICIMOD's member countries and representatives from universities and the private sector, including international organizations such as FAO and ISRIC – World Soil Information, to discuss on ways to improve the knowledge on soil science to contribute to the SDGs.

There was an urgent need to identify the gaps in current scientific research related to soils and identify pathways for ICIMOD to play a more prominent role to support national and transboundary initiatives on land management and soil conservation. As such, this workshop also outlined a set of actions specific to the HKH that will delineate current mitigation and adaptation needs. Outcomes from this workshop will be used as input to develop a full-scale soil proposal for the region, possibly as early as 2019.

The consultation was also provided a platform to discuss soil management practices and explore how they can help meet related SDGs while addressing climate change and stipulations from the Paris Agreement.

The consultation was focused on major five thematic areas, all of which are equally important to meeting the objectives stated above:

- **Soil fertility:** Sustainable mountainous agriculture; soil fertility in the mountain soil; conserving soil nutrients—best practices and indigenous knowledge; effects of intensive agricultural practices
- **Soil erosion and degradation:** Issues of soil degradation; soil erosion dynamic; soil degradation and erosion triggered by natural and human factors (landslides, mudslides, earthquakes, climate warming, frozen soil melts, deforestation, overgrazing, intensive agriculture, desertification, and land use change)
- **Watershed management:** Principle and practices of watershed management; water cycles; eco-hydrology of forests, rangelands and wetlands; upstream and downstream linkages
- **Climatic variability in soil management:** Information on Soil Organic Carbon (SOC) stock and its spatial distribution, temperature and precipitation variability; climate change adaptation and mitigation; soil dynamics under snow cover
- **Soil information system:** Relevance of soil information in addressing food security, climate change and sustainable management of land and water

Workshop procedures

Inauguration session

The program started with welcome remarks from **Dr David James Molden**, Director General, ICIMOD. In his welcome remarks, he described ICIMOD's area of work and emphasized the importance of this workshop in the context of climate change as well as the impact of climate change on Himalayan mountain soils. Climate change has increasingly influenced the stability of fragile mountain ecosystems and the livelihoods of 210 million people. ICIMOD is working for sustainable and resilient mountain development to address big challenges in the region in an integrated manner. Dr Molden noted that many changes are taking place in the HKH due to rapid population growth, economic development, urbanization, together with climatic change and variability, putting the ecosystems at risk. He also highlighted shifting cultivation as a key issue in some areas within the HKH. He said that often, local communities resort to clearing and burning forests to sustain food security. This action is not only changing the land use pattern but also adversely affecting soil-physical, chemical and biological properties. These changes not only pose challenges but also provide the opportunity to find solutions through a sustainable and integrated approach. In an integrated approach, not only soil experts from international organizations but also governmental institutions along with the communities come together to find solutions. Dr Molden further explained the significance of soil in the mitigation of climate change through C sequestration. Hence the role of soil in dealing with deforestation, change in land use, degradation, flood, etc., combined with the climatic variations, is crucial for the sustainable management of ecosystems. Though ICIMOD did not focus on the soil element earlier, it is now time to pay special attention to soils of the HKH region.

The background and purpose of the 'Joint BMUB-ICIMOD Expert Consultation Workshop on Hindu Kush Himalayan Mountain Soils' was presented by **Dr Thomas Strassburger**, Policy Officer (on Soil Protection), Unit WR III 2, Soil Protection and Remediation, Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Germany. Emphasizing the collaboration between BMUB and ICIMOD, Dr Strassburger mentioned the 2016 ministerial meeting of BMUB and Government of Bhutan during which they tried to find common ground for collaboration and forest management. A follow-up meeting in 2017 agreed to use the regional platform of ICIMOD to organize an experts' workshop on mountain soils.

The keynote address was delivered by **Dr Akhileswar Lal Karna**, Director General of the Department of Soil and Watershed Conservation Management, MoFE, Nepal. In his remarks he highlighted the fragility of the younger mountains of the HKH region. He explained that Nepal is more susceptible to soil erosion due to topographical, geomorphological, hydro-meteorological and anthropogenic causes. He talked about the grasslands of Mustang district and the Tarai region and unscientific agricultural practices. In his note, he underlined the need to document knowledge for proper implementation of soil management. He also said that outputs of this workshop can be useful in soil management at the local, provincial and central level in Nepal.

In the context of the Hindu Kush Himalaya, **Dr Eklabya Sharma**, Deputy Director General, ICIMOD, discussed the existing farming systems of the HKH region and soil heterogeneity of the mountain area. He said that ICIMOD has prioritized soil conservation, and that the workshop on soils was a timely event. He highlighted various issues related

DG, ICIMOD delivering the welcome speech

Dr Thomas Strassburger, Policy Officer on Soil protection from BMUB conveying objective of the workshop

Dr Akhileswar Lal Karna DG, DSCWM, delivering key note speech

Dr Eklabya Sharma, DDG, ICIMOD setting the HKH context to soil degradation ranging from natural causes to anthropogenic disturbances. He also acknowledged traditional ways of soil fertility management in the HKH region.

Technical sessions

The 18 research papers presented during four technical sessions that broadly fell under five thematic areas (Table 1).

Table 1: **Papers presented at the workshop**

c	Thematic Area	Topics	Presented by	Organizations
1	Soil fertility management	Soil fertility on mountain soils	Ms Lucrezia Caon	Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, Roma
2		Nutrient cycle to address food security	Mr Kamal Sah	Soil Science Division, Nepal Agricultural research council, Nepal
3		Soil Fertility Management for Sustained Crop Production in Gilgit-Baltistan, the Northern Mountainous Region of Pakistan	Mr Sher Ahmed	Mountain Agriculture Research Centre (MARC), Pakistan
4		Intensive Agricultural Practices in Nepalese Hills Contributing to Soil Quality Decline and Emissions Increase	Dr Nani Raut	Kathmandu University, Nepal
5		Addressing the Issues of Land Degradation: A Nutrient Management Perspective	Dr Rajendra Gautam	Samriddhi Agricultural Research and Development Pvt. Ltd., Nepal
6	Soil erosion and degradation	Soil degradation and dwindling ecosystem services in the HKH: A case from Tibetan rangeland	Prof. Ruijun Long	International Centre for Integrated Mountain Development (ICIMOD)
7		Soil degradation and challenges in land reclamation in the Indian Himalayan region	Dr Vijender Pal Panwar	Indian Council of Forestry Research and Education (ICFRE), GoI
8		Estimation of Soil Erosion Dynamics in the Koshi Basin Using GIS and Remote Sensing	Mr Kabir Uddin	International Centre for Integrated Mountain Development (ICIMOD)
9		Issues of mountain soil degradation in Myanmar	Ms Swe Swe Tun	Forest Research Institute, Myanmar
10		Changes in soil physical properties of forest floors in landslides caused by the Wenchuan earthquake	Prof. Gang Yang	School of Life Science and Engineering, Southwest University of Science and Technology
11	Watershed management	Principle and practices of watershed management in Nepal: A walk to reverse mountain soils degradation	Mr Kishor Aryal	Department of Soil and Watershed Conservation Management, MoFE Nepal
12		Soil Function: Infiltration and Recharge	Dr Prasanta Kumar Mishra	ICAR- Indian Institute of Soil and Water Conservation Dehradun, India
13	Climatic variability in soil management	Review on Status of Soil organic carbon (SOC) and other nutrients in Hind Kush Himalaya	Dr Himlal Shrestha	International Centre for Integrated Mountain Development (ICIMOD)
14		Digital Soil Mapping of Soil Organic Carbon Stock in Bhutan	Dr Tshering Dorji	National Soil Services Centre (NSSC), Department of Agriculture, Ministry of Agriculture and Forests, Bhutan
15		Livestock and soil management in the Qinghai-Tibetan Plateau	Prof. Huai Chen	Chengdu Institute of Biology, Chinese Academy of Sciences
16		Estimation of Carbon Stock of Grassland Ecosystems in The Hindu Kush Himalayan Region	Prof. Yanbin Hao	University of Chinese Academy of Sciences, China
17		Sustainable management of soil carbon and fertility in mountain area under the rapid land alteration routine based on the case study of grassland ecosystem in the Qilian mountain	Prof. Zhanhuan Shang	School of Life Sciences, State Key Laboratory of Grassland Agro-ecosystems, Lanzhou University, Lanzhou, China
18		Soil dynamics under snow cover and climate change	Dr Lin LIU	Sichuan Agricultural University, Chengdu, China
19	Soil information system	Soil Information for Food Security, Climate Change and Sustainable Management of Land and Water	Dr Jan de Leeuw	Land Conservation, ISRIC – World Soil Information

Panel discussion was organized after each presentation to discuss key challenges and gaps. Group work was carried out to identify and prioritize key issues and challenges together with strategies to overcome those challenges (Table 2). The strategies were guided by activities recommended by the working groups for improving integrated soil management in the region. ICIMOD being a regional organization was requested to facilitate the south-south co-operation by implementing those strategies.

Table 2: **Key issues and challenges, gaps and strategies on HKH soil managemen**

Sn	Key issues and challenges	Gaps	Strategy to overcome the gap (mitigate)
Nutrient loss			
1	**Cropland**		
	• Imbalance in fertilizer use (balancing NPK), eutrophication, acidification and leaching in intensive systems, nutrient mining and deficiencies in extensive systems. • Limited fertilizer availability. Lack of crop rotation and legumes. • Limited adoption of sustainable land management (SLM). • Short land tenure. • Limited awareness and technical support.	• Lack of proper nutrient management (overuse or underuse of fertilizers, nutrient mining) • Inadequate policy for land use, land tenure agricultural intensification • Lack of incentives and lack of technical support. • Inadequate institutions.	• Code of conduct for the management of fertilizers (CoCoFe, FAO). • Integrated nutrient management • Policy development for land use, land tenure and agricultural development and intensification. • Implement land use policies if not implemented yet. • Strengthen related institutions.
2	**Rangeland**		
	• Nutrient deficits due to nutrient mining (burning), land degradation leaching (washing away nutrients), and overgrazing.	• Absolute lack of rangeland nutrient management policies and plans (not on the radar). • Lack of scientific insight on how much rangeland livestock production could be improved with proper nutrient management.	• Development of rangeland nutrient management plans and policies and scientific research to support this.
3	**Data availability**		
	• Inconsistency in methodologies and data availability	• Methodology is different so harmonization required	• Implementation of regional program for harmonization of lab methods and data (SEALNET, FAO) • Updated instrumentation
Soil erosion and degradation			
4	**Cropland**		
	• Significant surface erosion. • Soil acidification. Salinization in irrigated systems. • Desertification. • Depletion of SOC affecting nutrient status.	• Lack of knowledge on land degradation status and its agricultural and socio-economic impacts, resulting in poorly focused policies.	• Mainstream and implement the UNCCD land degradation neutrality (LDN) approach at national to local level, review soil degradation status, develop adequate policies and target appropriate interventions. • Implement the Voluntary Guidelines for Sustainable Soil Management (VGSSM)
5	**Rangeland**		
	• Overgrazing • Reduced rangeland production • Non-palatable species • Invasive species • Reduced livestock production • Degradation of biodiversity • Irreversible seed bank changes	• Most countries haven't assessed carrying capacity for livestock and livestock development policies that are based on outdated information from the past century.	• Develop GIS based carrying capacity assessments and guide policies with up-to-date information on sustainable stocking densities. • Learn from neighbouring countries (China).
6	**Data availability**		
	• Getting the data on soil and land use parameters	• Universal classification and mapping system is lacking.	• Regional cooperation (research/ hearing/ sharing) • Conduct research on the capacity of the rangeland.
Water conservation			
7	**Cropland**		
	• Seasonal distribution of water (over-supply in summer and shortages in winter). • Water quality in winter below standards for use in agriculture and consumption.	• Interest in investing in water infrastructure has dwindled. Lack of soil and water conservation by farmers.	• Improved seasonal water availability. • Invest in irrigation infrastructure. • Apart from large-scale irrigation, stimulate local on-farm soil and water management.

8	**Rangeland**		
	• Instability of permafrost soils due to climate change. • Climate change will influence rangelands, water, livestock nexus (though impacts are not clear).	• Knowledge gap on the future of water related constraints for high mountain livestock production due to climate change.	• Policy research on water, rangeland livestock nexus.
9	**Conservation of water quantity and quality**		
	• Water quantity and quality	• Climate change • Water storing system for drinking/irrigation • Population pressure	• Climate change adaptation and management • Water recharge measure • Conservation at source • Plant more water use efficient crops –directly proportional to financial gain from the plant • Water use (Efficient irrigation systems)- drip irrigation
	• Lack of required data/information	• Inventory and utilization of water resources information are lacking.	• Map for natural springs (dying, perennial and dead spring) • Rejuvenation of springs

Closing session: Follow-up and next steps

In his remarks **Dr Eklabya Sharma**, Deputy Director General, ICIMOD, said that ICIMOD needs to think in a focused manner about soil management in relation to mountain farming system. He also underscored the need to harmonize existing soil classification and understand soil in the HKH region. Dr Sharma said this workshop was a starting point for networking with soil institutions and soil scientists of the HKH and that this process will be continued in the coming days. He expressed appreciation for BMUB's support in organizing the workshop, adding that ICIMOD would be interested to collaborate further for improving soil management in the HKH region.

Dr Thomas Strassburger requested ICIMOD to draw attention to issues related to soil management and create a platform for highlighting the role of soils in mountain ecosystems. He said it is important for HKH member countries to co-operate and motivate each other and share information and resources and knowledge in order to deal with problems in soil management. Though research is limited, experts of this region have enough data to push policymakers to focus their vision on soil management. Finally, he suggested implementing and scaling up good practices in the region.

In his concluding remarks, **Dr David Molden**, Director General, ICIMOD, recognized soil as a major issue that should be discussed continuously. There are many challenges related to soil, food security and so on. Therefore, ICIMOD will try to prepare a special report on soils in the HKH region and come up with action plans in the near future.

Finally, the workshop was ended with a vote of thanks from **Dr Bhaskar Karky**, Programme Coordinator, Regional REDD+ Initiative, ICIMOD.

Conclusions

This workshop was jointly hosted by ICIMOD and BMUB. It was the first meeting on mountain soils in the HKH region. The workshop brought together soil scientists from ICIMOD's six regional member countries and additional experts from FAO and ISRIC, supported by GIZ. During the workshop, BMUB and ICIMOD experts outlined main challenges, identified major gaps, and suggested strategies to overcome those gaps so that mountain soil and its nutrients could be conserved, managed, and enhanced. The recommendations that this workshop came up with apply to the entire Hindu Kush Himalayan region.

This document may be used in multiple ways. It can be a starting point for more detailed research in one of the specific areas included in the recommendations or it can be used by agencies working on soils to develop a specific proposal. The papers presented at the workshop are a valuable source of knowledge and reflect the authors' rich experience in soil-related issues in the region. ICIMOD has been requested to coordinate and facilitate a regional initiative to address soil related issues in the HKH region by forging partnerships with appropriate institutions and government agencies. Furthermore, the following concern have been emphasized:

- Data and practices related to studying mountain soils in the HKH remain unharmonized
- Overall assessment shows that HKH soils in all land use types are degrading
- Current rehabilitative or maintenance measures appear to be based on silo-approach and may be causing more degradation than betterment of soils
- Current soil classification and analytical systems are not harmonized and hence data comparability in HKH is limited
- The adoption of integrated watershed management can contribute to reducing land degradation and better managing water quality and quantity
- Documenting the best practices for soil management in the HKH region and sharing this knowledge at the policy and local levels can mitigate these consequences. The establishment of a south-south learning and sharing platform will improve knowledge sharing across the HKH region and contribute to this.

Way Forward and Recommendations

At the workshop, the experts from the region presented papers on issues and challenges in improving soil management and conservation in the mountain areas of the HKH region. Based on those challenges, the group made the following recommendations. ICIMOD has been asked to coordinate the recommendations where feasible in collaboration with appropriate partners.

1. Manage nutrient dynamic

Cropland is facing a number of challenges such as limited fertilizer availability, imbalance in fertilizer use (balancing NPK and micro nutrients), eutrophication, acidification and leaching in intensive systems, nutrient mining and deficiencies in extensive systems. Economic and integrated nutrient management will help to revive nutrient loss in the HKH region. Apart from documentation and field demonstration, awareness and capacity building is also necessary. Moreover, code of conduct for the management of fertilizers (CoCoFe, FAO) at the local, national and regional level should be established.

Rangelands in the HKH region are threatened by nutrient deficits due to nutrient mining (burning), land degradation leaching (washing away of nutrients), and overgrazing. Scientific research can provide insight on how integrated soil nutrient management could improve livestock production. Furthermore, rangeland nutrient management plans and polices should be developed and implemented to ensure improved livestock production.

2. Effective land management

Cropland should be managed sustainably with a legume based cropping system, applying an appropriate amount of fertilizer at the right time. Proper soil testing based on the crops and cropping system, adequate infrastructure and information and technical support for farmers should be made available. Additionally, identifying and including local indigenous knowledge in conservation measures is equally important.

Rangelands of the HKH are facing problems of overgrazing, reduction in production, non-palatable species, invasive species, loss of biodiversity and irreversible seed bank changes. Moreover, livestock development policies should be updated using GIS based technology for assessing carrying capacity and sustainable stocking densities.

3. Adopt appropriate land tenure

In some countries in the HKH region, short land tenure makes it difficult to promote the adoption sustainable land management. It is important to develop agriculture and land use policy with appropriate land tenure management in the countries (Myanmar), and implement these policies in countries where such policies are not in place.

4. Filling the knowledge gaps on soil nutrients

There is a lack of data on soil nutrients and fertilizers used in conventional and modern agriculture system in the HKH region. Further, available data is not validated through laboratory analysis, without which it is difficult to make decisions on improving soil nutrients management. Limited awareness among farmers, limited technical support and financial constraints also pose a challenge. Therefore, efforts should be made to fill essential knowledge gaps and to disseminate existing knowledge.

5. Monitoring and rejuvenation of water resources

Cropland in the HKH is facing seasonal variation in water; over-supply in summer and shortages in winter. Hence appropriate soil and water conservation practices should be followed to ensure improved seasonal water availability. Further, there is a need to promote investment in large-scale irrigation infrastructure.

Rangeland bears unstable permafrost soils due to the effects of climate change. The quantum of impact on future water availability and livestock production is not yet known. Therefore, policy research should be conducted on water and livestock nexus in the rangeland of high mountains in the HKH.

Rejuvenation of natural dying, perennial and dead springs can ameliorate the impact of climate change on water resources in mountainous areas. Proper inventories of dying, perennial and dead springs should be developed; appropriate management measures should be implemented to revitalize springs.

6. Integrated watershed management to prevent erosion and manage water quality and quantity

Soil erosion is a common and growing problem in the HKH region. It can be minimized through adapting integrated watershed management techniques. For that, it is necessary to determine the land degradation status and its impact. Potential soil erosion through natural and anthropogenic activities should be evaluated to identify the hotspots. Moreover, piloting upstream-downstream linkages in selected watersheds can help reduce soil erosion.

Water quality and quantity depends on seasonal variation. Proper conservation measures at the source of silt and sediment production will enhance water quality in the downstream. In order to improve water quantity, the water recharge function should be improved through local and modern technologies.

7. Improvement of soil health to mitigate and adapt to climate change

There is limited documentation of soil health in the HKH region; therefore soil health should be continuously monitored and assessed using physical, chemical and biological indicators. Soil organic carbon, biodiversity status and microbial biomass are important soil health parameters. Avoiding deforestation and forest degradation, conservation of forest carbon, adopting sustainable forest management and enhancement of forest carbon will also improve soil health.

8. Incentives to success stories in the HKH

Education, awareness and capacity building of people will help avert the consequences of climate change in the HKH region. Incentives should be provided to people for carrying out good practices in soil, water and vegetation conservation and to scale up technologies to the sub-national, national and regional level.

9. Establishment of rural-urban linkage

The socio-economic status of the rural population should be maintained through provision of basic services such as education, healthcare and daily necessities. Cross-sectoral policies should be formed and implemented in a sustainable manner to improve the livelihood of the rural population in the HKH. For example, development of livestock and crops with value chains that link urban areas to rural areas. In particular, value chains of meat and milk products can be developed so that such products can find a market in urban areas. This will create employment opportunities and improve livelihoods, contributing to the well-being of the highland people. The successful co-operation among Alpine countries (e.g., Switzerland, Austria) in the livestock sector can be replicated in the HKH.

10. Regional co-operation

South-South learning platform

- Establish a soil experts' network in the HKH for developing uniform standards (nutrients, soil and water), guidelines and proposal for policy making.
- Network on mountain soils, linkage with the Global Soil Partnerships.
- Synchronize the information based on baseline scaling covering major ecosystems in the HKH
- Harmonize methodology and lab techniques

- Uniform soil classification system
- Establish a long-term monitoring system for climatic parameters and soil properties

Mainstreaming effective tools and technologies

- Implement a regional programme for harmonizing lab methods and data sets (SEALNET, FAO); policy development and extension work
- Implement Voluntary Guidelines for Sustainable Soil Management (VGSSM)
- Implement the UNCCD, land degradation neutrality (LDN) approach at the national to local level, review the soil degradation status, develop adequate policies and implement appropriate, target-oriented interventions.
- Analyze the economy of soil degradation linking to FAO and Global Soil Partnership (GSP)
- Enable the framework for policies on new code of conduct for all land use.

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Annex 1: Programme of expert consultation workshop

Time	Event	Organization	Speaker	Facilitator
Day One: Inauguration (20 March, 2018)				
09:00-09:30	Arrival and registration			
09:30-09:40	Welcome Remarks	DG, ICIMOD	Dr David Molden	
09:40-09:50	Objective of the workshop	• Policy Officer (on Soil Protection), • Unit WR III 2, • Soil protection and Remediation, Federal Ministry for the Environment, Nature • Conservation, Building and Nuclear Safety	Dr Thomas Strassburger	
09:50-10:00	Key note	• DG, Department of Soil Conservation and Watershed Management, Nepal	Dr Akhileswar Lal Karna	
10:00-10:15	Setting the Hindu Kush Himalayan context	DDG, ICIMOD	Dr Eklabya Sharma	
10:15-10:40	**Group Photo and Tea Break**			
10:40-10:50	Introduction of Participants			
Day One: Technical Session (20 March, 2018)				
10:50-11:10	Presentation: The relevance of soil information in addressing food security, climate change and sustainable management of land and water	International Soil Reference and Information Centre (ISRIC – World Soil Information)	Dr Jan de Leeuw	Mr Kai Windhorst
11:10-11:15	Questions and Answers			
11:15-11:35	Presentation: Soil degradation and dwindling ecosystem services in the HKH	ICIMOD	Prof. Ruijun Long	
11:35-11:40	Questions and Answers			
11:40-12:00	Presentation: Status of Soil organic carbon (SOC) and other nutrients in Hindhu Kush Himalaya	ICIMOD	Dr Himlal Shrestha	
12:00-12:05	Questions and Answers			
12:05-12:15	Plenary discussion			
12:15-13:15	**Lunch**			
13:15-13:35	Presentation: Soil degradation and challenges in land reclamation in the Himalaya region	Indian Council of Forestry Research and Education (ICFRE), GoI	Dr Vijender Pal Panwar	Dr Rajan Kotru
13:35-13:40	Questions and Answers			
13:40-14:00	Presentation: Infiltration and recharge: as a soil function	Institute of Soil and Water Conservation, Dehra Dun, GoI	Dr P.K Mishra	
14:00-14:05	Questions and Answers			
14:05-14:25	Presentation: Nutrient cycle to address food security	NARC: Nepal Agricultural research council, Nepal	Mr Kamal Sah	
14:25-14:30	Questions and Answers			
14:30-14:40	Plenary discussion			
14:40-15:00	**Break**			
15:00-15:20	Presentation: Status of soil carbon in forest and Agricultural field, Bhutan	National Soil Service Centre (NSSC), Bhutan	Dr Tshering Dorji	Dr Bhaskar Singh Karky/ Mr Kai
15:20-15:25	Questions and Answers			
15:25-15:45	Presentation: Principle and practices of watershed management in Nepal	Department of Soil Conservation and Watershed Management, Nepal	Mr Kishor Aryal	
15:45-15:50	Questions and Answers			
15:50-16:05	Understanding Sediment Management in Koshi River Basin		Mr Kabir Uddin	
16:05-16:10	Questions and Answers			
16:10-16:30	Plenary discussion: Identification of key issues			
18:00-21:00	Reception dinner for all participants at Babarmahal Villas			

Time	Event	Organization	Speaker	Facilitator
Day Two: Key challenges, gaps and strategies (21 March, 2018)				
Pick up from Hotel Himalaya reception at 8:15				
09:00-09:15	Recap of discussions from first day and introduction to second day			Mr Clemens Kunze
09:15-09:35	Presentation: Why soil fertility matter in the mountains	FAO: Global Soil Partnership, Land and Water Division	Ms Lucrezia Caon	
09:35-09:40	Questions and Answers			
09:40-10:00	Presentation: Soil management practices for mountain farmers	Pakistan	Mr Sher Ahmed	
10:00-10:05	Questions and Answers			
10:05-10:25	Presentation: Livestock and soil management in the Qinghai-Tibetan Plateau	Chengdu Institute of Biology, Chinese Academy of Sciences, China	Prof. Chen Huai	
10:25-10:30	Questions and Answers			
10:30-10:40	Plenary discussion			
10:40-10:50	**Break**			
10:50-11:10	Presentation: Intensive agriculture contributing to soil degradation and climate warming in Nepal hills	Kathmandu University, Nepal	Dr Nani Raut	Prof. Ruijun Long
11:10-11:15	Questions and Answers			
11:15-11:35	Presentation: Issues of mountain soil degradation in Myanmar	Researcher, Forest Department, Myanmar	Ms Swe Swe Tun	
11:35-11:40	Questions and Answers			
11:40-12:00	Presentation: Estimation of carbon storage in HKH grassland soils	University of Chinese Academy of Sciences, China	Prof. Yanbin Hao	
12:00-12:05	Questions and Answers			
12:05-12:15	Plenary discussion			
12:15-13:15	**Lunch**			
13:15-15:15	Group works (three): Developing strategies for addressing key challenges to maintain ecosystem services through soil management (Key challenges, Gaps and Strategies)			Dr Thomas / Dr Jan de Leeuw / Ms Lucrezia / Prof. Long
15:15-15:35	**Break**			
15:35-16:15	Workshop summary: Group presentation on strategies			Dr Bhaskar / Mr Kai
16:15-16:25	Follow-up and next steps	BMUB and ICIMOD		Dr Thomas and Dr Eklabya
16:25-16:30	Vote of thanks	ICIMOD		Dr Bhaskar

Annex 2: List of participants

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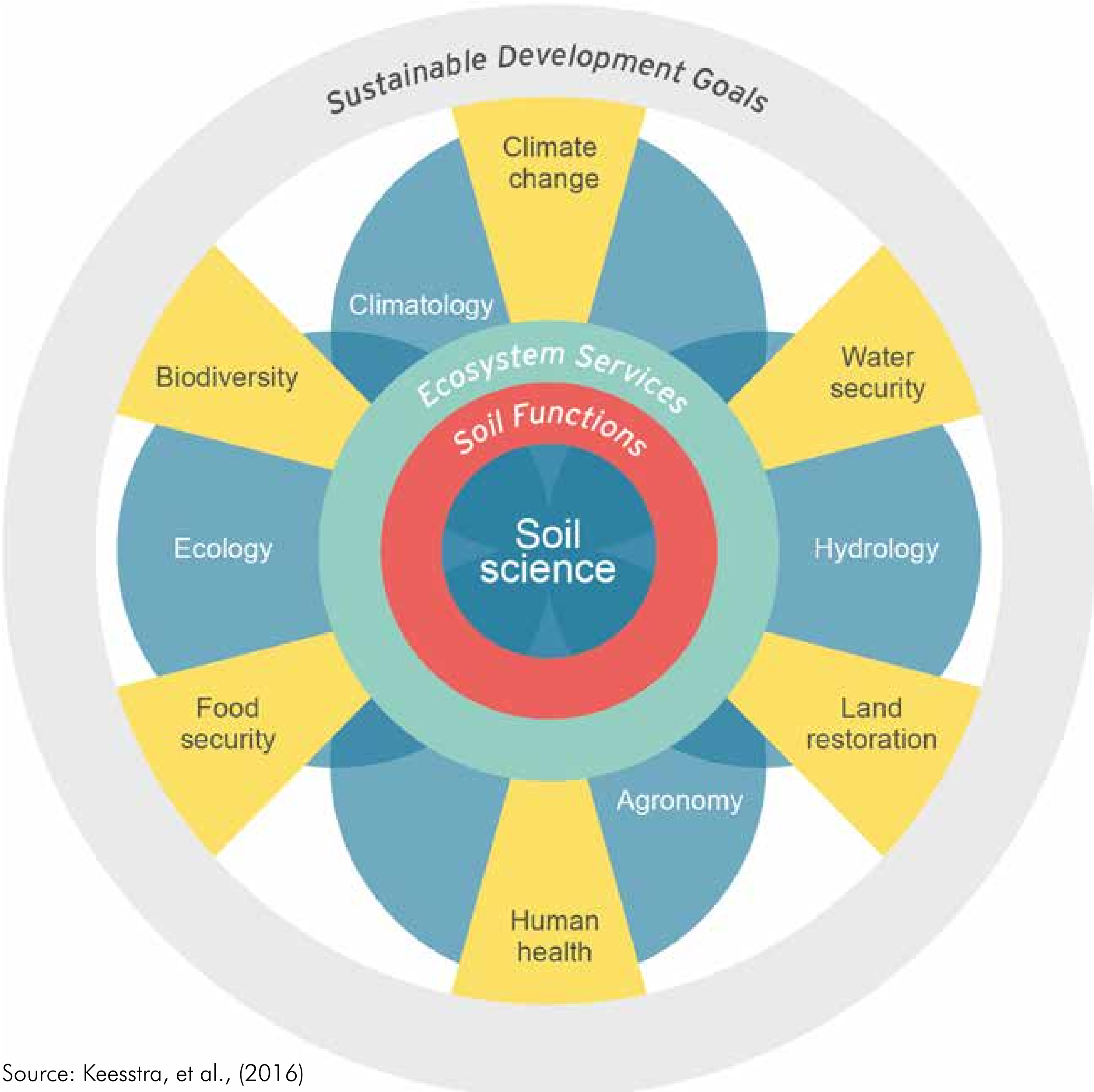
Annex 3: Proceeding papers

Theme: Soil fertility management

Conserving mountain soil fertility is an urgent matter

- Mountain soils are fragile and affected by deforestation, overgrazing, expanding population and poor infrastructure.
- Mountain soils are very sensitive to land use and climate change, which exacerbate soil degradation processes leading to a decrease in soil fertility.
- Soils contribute to human health, water conservation, food security, climate change, land restoration, biodiversity and other SDGs.



Source: Keesstra, et al., (2016)

Soil fertility in mountain soils

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Abstract

Soil fertility can be preserved and enhanced by practicing sustainable soil management as recommended in the Voluntary Guidelines for Sustainable Soil Management (VGSSSM), investing in the development of tools to assess, monitor and interpret data on the soil nutrient content, and ultimately by investing in awareness raising activities and capacity building. The GSP has a well-developed strategy to tackle soil fertility related problems in mountain areas globally and in Asia especially.

Introduction

Mountain soils are generally defined as poorly developed, skeletal and shallow, mainly because the low temperatures limit biogeochemical activities, slowing down soil genesis and evolution. Their distribution is subject largely to vertical zonation and their soil nutrient availability for crops differs along slopes and with increasing elevation. Because soil properties, plant species and productivity vary at a small scale in mountains, it is proper to talk about altitude-specific nutrient limitations for different crops. Generally, soil fertility decreases as elevation increases and it is absent on rocky peaks and ridges. Mountain soils are usually poor in nitrogen, and soil pH, soil available phosphorus, exchangeable potassium, calcium and magnesium decrease with elevation. In this context, agricultural activities generally take place at intermediate elevation classes while pastoralism is practiced at higher altitudes (FAO, 2015a; Kohler, Wehrli and Jurek, 2014).

The large amount of primary minerals makes intra-soil weathering very important in the formation of mountain soils. This is true especially in warm and humid climates where weathering is intensive and can also lead to an increase in nutrient leaching. The link between soil fertility in mountain soils and the orographic rainfall gradient makes mountain soils very sensitive to climate change (Hagedom et al, 2010; FAO, 2015a). According to Hagedom et al. (2010), mountain ecosystems are currently experiencing the strongest climatic warming and the largest changes in land-use since the last millennia. In fact, most of the world's mountain regions are warming twice as fast as the global average with major consequences on microbial activities and the nitrogen/phosphorus ratio; temperature warming increases nitrogen but have no effect on phosphorus (Mayor et al., 2017). Consequently, plants that thrive at lower elevations will quickly move up the mountains where the supply of nitrogen is growing because more organic matter is decomposed by microbes. However, studies carried out in Germany showed that increased microbial activities could also lead to a decline in the soil organic carbon content (Mayor et al., 2017).

Although the impacts of climate and land-use changes on the soil nutrient and carbon cycles are largely unknown (Hagedom et al, 2010), hazards such as floods, landslides, debris flows and glacial lake outbursts are on the rise in most mountain regions where the increased frequency of extreme events causes heavy rainfall, droughts and glacier melt. The most vulnerable mountain areas are those affected by deforestation and overgrazing, and those with rapidly expanding populations and poor infrastructure (FAO, 2015a; Kassa et al., 2017). Under these conditions, extreme weather events can increase the risk for soil erosion, loss of soil organic carbon, loss of soil biodiversity and soil nutrients depletion, ultimately leading to a decrease in soil fertility.

In a world in which three-quarters of the poor depends on agriculture, soil fertility matters. It is the component of overall soil productivity and a key ally against famine worldwide. According to the State of Food Security and Nutrition in the World 2017 (FAO et al., 2017) and the State of Food and Agriculture 2017 (FAO, 2017a), world hunger is on the rise again and undernourished people increased to 815 million in 2016. Famine leads to the displacement of 26.4 million each year and to the international migration of 244 million people. In this context, preserving and increasing soil fertility through sustainable soil management, which could produce up to 58% more food, can help in addressing world hunger.

How to manage soil fertility in the mountains

Mountain soils are fragile but their fertility can be preserved through the practice of sustainable soil management. According to FAO (2015b), "soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity. The balance between the supporting and provisioning services for plant production and the regulating services the soil provides for water quality and availability and for atmospheric greenhouse gas composition is a particular concern".

Soil fertility can be preserved and enhanced by putting into practice the principles in the revised World Soil Charter (FAO, 2015b) and the recommendations in the Voluntary Guidelines for Sustainable Soil Management (FAO, 2017b). For instance, the introduction of new crops in the crop rotation, the application of green manure, mulching, composting, the reduction of land-use change (conversion of natural forest into cropland), the construction of terraces and the establishment of agro-forestry systems can help in minimizing the risk for soil nutrient depletion, soil organic carbon loss, soil biodiversity loss and, last but not least, soil erosion. In addition, local fertilization strategies should be developed building on soil nutrient assessments and by looking at specific crop requirements (FAO, 2015a; FAO, 2017c). In this regard, it is important to base fertilizer recommendations on the analysis of good quality soil laboratory data.

In November 2017, the Global Soil Laboratory Network (GLOSOLAN) was established under the umbrella of the Global Soil Partnership (GSP) with the purpose of harmonizing soil laboratory methods and data so as to ensure data quality and promote data exchange at all levels (FAO, 2018a). To implement GLOSOLAN in the Asia region, the South-East Asia Soil Laboratory Network (SEALNET) was established. Since its first meeting in November 2017, SEALENT is working to (1) calibrate and harmonize soil testing procedures and practices in laboratories in the ASEAN and wider Asia regions in the context of the Asian Soil Partnership, and (2) set up a regional inter-laboratory proficiency program to implement QA/QC procedures and processes (FAO, 2018b).

SEALNET is only one of the many activities that aim to sustainably manage soil fertility in the Asian Soil Partnership implementation plan, a document compiled by more than one hundred soil experts from the twenty-four countries forming the Asian Soil Partnership (FAO, 2016). According to the regional experts, soil fertility-related problems in Asia could be tackled by:

- Identifying priority areas for soil fertility management and causes for soil nutrient imbalance and crop failure;
- Updating and promoting the soil fertility maps under different land use systems;
- Developing GIS based soil fertility assessment;
- Using remote sensing and GIS technology to relate nutrient assessment and recommendations to landscape analysis;
- Developing soil spectra based fertilizer recommendations system;
- Launching e-village soil fertility management initiatives for fast and remote dissemination of technologies and information;
- Establishing on-farm demonstrations on improved soil management practices counting on the application of organic matter, biochar, and organic and inorganic fertilizers;
- Establishing an online soil counseling clinic for imparting knowledge on SSM practices, soil information systems, soil characteristics and functions, soil suitability to crops, soil fertility and crops requirements (water and nutrients), and soil resilience to climate change;
- Producing/updating national guidelines on fertilizer application. Guidelines should inform and advise on (i) integrated nutrient management approach and techniques, (ii) fertilizer recommendations systems based on soil test crop response, (iii) development of fertilizer prescription equations for major crops in different agro climatic conditions and land use systems, (iv) nutrient dynamics in different soils, (v) harnessing nutrient interactions for upscaling use efficiency, (vi) enhancing soil organic matter content, (vii) ameliorating soil acidity, (viii) soil-plant-animal continuum to diagnose mineral disorders, and (ix) fertigation;
- Developing a technical manual on nutrients imbalance;
- Developing Site Specific Integrated Plant Nutrient Supply (SSIPNS) modules for sustainable productivity;
- Developing tools for decision making on fertilizer application at the field level;
- Developing a software for district wise fertilizer recommendation and dissemination for major crops;

- Providing soil analysis services using a soil testing kit (previously standardized), giving preliminary recommendations for soil and fertilizer management to members and others in the community;
- Demonstrating precision management and comparing it to traditional management;
- Compiling requests for fertilizer and soil amendments from members as recommended, and ordering and distributing them accordingly;
- Developing sensor technology to monitor nutrients in soil;
- Using forecasting models to develop Artificial Neural Networks (ANN) providing recommendations on nutrient management;
- Developing ready Reckoner of lime and fertilizer recommendations for ready access and dissemination of fertilizer schedule for major nutrients;
- Finding knowledge gaps for identifying/developing indicators for assessing the economic cost of soil degradation and the value of its rehabilitation (stocks taking and gaps analysis). Indicators might be developed considering: (i) soil resources within the framework of ecosystem services, particularly soil functions/soil ecological services, (ii) high-value crops productivity (e.g. rice, oil palm, and others), (iii) nutrient use, nutrient uptake, fertilizer nutrient use efficiency, nutrient loss and soil mining, (iv) nutrient content of high-value crops in relation to their yield, (v) quantification of yield losses under various land use systems, (vi) soil biodiversity/the role of soil biota towards soil rehabilitation/restoration, (vii) micro nutrients of the soil and the high-value crops, (viii) the content of heavy metals and other toxic substances in high-value crops, and (ix) established limits in the content of heavy metals and other toxic substances for crops entering international markets;
- Standardizing soil test interpretation for site specific nutrient management;
- Organizing a workshop for standardization of soil test interpretation for RSP. Organize regional and international conferences and workshops to promote soil testing and quality control assessment; and
- Building on recommendations from stakeholder consultations, create guidelines for extension officers to transfer site-specific nutrient management (SSNM) knowledge, technologies and organizational management practices to community soil and fertilizer management centers (CSFMCs).

In order to support the implementation of activities on soil fertility at the regional level, the GSP is ultimately leading the development of a Code of Conduct for the Management of Fertilizers (CoCoFe). The CoCoFe aims to (1) increase global food production on current agricultural land, (2) maximize the efficient use of plant nutrients to enhance sustainable agriculture, (3) minimize the environmental impacts of the use of fertilizers including pollution by loss of nutrients via runoff, leaching, greenhouse gas emissions and other mechanisms; and reducing the effects of non-nutritive constituents on soil, animal, and human health, (4) maximize the environmental benefits of using fertilizers including reducing the need for additional land to be brought into production, increased carbon storage in soils, and improvements in soil health, and (5) maintaining and improving food safety and nutrition (FAO, 2018c).

Education and capacity building also play a central role in the sustainable management of natural resources, including of non-renewable ones like soil. The need to educate and train land users on sustainable soil management is increased by the fact that around 45% of mountain areas are not or only marginally suitable for growing crops, raising livestock or carrying out forestry activities (Kohler, Wehrli and Jurek, 2014). In 2017 the GSP gave great importance to launching awareness raising campaigns, developing programmes to educate farmers on SSM such as the “Global Soil Doctors”, organizing international events and investing in digital soil mapping trainings on parameters critical to soil fertility such as soil organic carbon. Activities culminated in the World Soil Day celebrations, where the first Global Soil Organic Carbon (GSOC) map produced using a bottom-up approach was launched (FAO, 2018d). This map is highly useful in planning activities at the national and local level and in reporting on global status and trends. In this context, the map will be also used in the Soil Atlas of Asia, a freshly launched activity of the GSP.

Conclusions

Mountain soils are very sensitive to land use change and climate change, which exacerbate soil degradation processes leading to a decrease in soil fertility. However, soil fertility in mountain areas can be preserved and enhanced by practicing sustainable soil management as recommended in the Voluntary Guidelines for Sustainable Soil Management, investing in the development of tools to assess, monitor and interpret data on the soil nutrient content, and ultimately by investing in awareness raising activities and capacity building. The GSP has a well-developed strategy to tackle soil fertility related problems in mountain areas globally and in Asia especially. The launch of global activities such as GLOSOLAN and the Global Soil Doctors will further support the implementation of activities in the Asian Soil Partnership implementation plan and help in fighting hunger in the most populated regions of the world, especially Asia.

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Nutrient cycle to address food security

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Abstract

In Nepal, more than 90% of cultivated land is under severe threat of carbon (<2% carbon by mass) depletion and soil acidity compounds the problem. The possible minor reasons behind food insecurity could be the small land holdings and low productivity. But the major reasons are lack of adequate and timely availability of fertilizers, young and immature soils (mostly Entisols and Inceptisols) and soil erosion in mountainous areas. The sustainable soil management programme could improve soil fertility through enhancement of the soil organic matter pool, which requires appropriate agricultural technologies for water and nutrient management including no till farming, compost and mulching, leguminous cover crops, water harvesting, agroforestry and integrated farming system along with judicious use of chemicals. Besides these, a holistic approach for managing soil health is necessary, and a comprehensive study covering all elements including micronutrients with site specific nutrient management should be conducted for the targeted crop with the inclusion of indigenous knowledge and expertise.

Introduction

Feeding the world's population, which is estimated to exceed 9.7 billion by 2050, presents a big challenge. The rising population will reach its peak of 10.9 billion by 2100 (United Nations, 2011). It is estimated that demand for food production will grow to 70 percent by 2050, with the current rate of population growth and changing food habits. In addition, we must be ready to face the problems of changing diets, increasing non-food demand for agricultural products, declining growth in agricultural production and productivity and uncertainties. There is increasing competition for critical resources such as land, biomass, energy and nutrient reserves (esp. phosphorus). Nitrogen is always a limiting factor of productivity. Carbon, a basis of soil life, is under threat due to extensive agriculture. In Nepal, the condition is more serious in the Terai region. More than 90% of cultivated land is under severe threat of carbon (<2% carbon by mass) depletion. Soil acidity is itself a hindrance to production. Around 55% of the country's cultivated land is under the threat of soil acidity.

Nepal is ranked 81st in food security among 113 indexed countries (Global food security index, 2015). More than 65% of the population in the mid-western hills, far-western hills, central and eastern mountains are chronically food insecure. The condition is more serious (75% of the population in chronic food insecurity) in the eastern mountains. The dependency on own production is low (only contributes 30%). More than 50% of food sources are purchased and the condition is more serious in urban areas (nearly 70% of purchased food sources) than in rural areas (around 45% purchased food source) (NLSS, 2011). There are many drivers of food security. Food production is one of the major drivers that are directly linked with food availability. In Nepal, cereals are more widely consumed (23-33% share in food consumption patterns) than other food sources (NLSS, 2011). Productivity trends for cereals seem to be increasing over the last decades. Still, there is less availability of food per capita. So, Nepal is in a transitional phase of food security. Fertilizer use per ha is increasing (1.4 kg/ha in 2008 increased to 73.8 kg/ha in 2014) but is still the lowest in South Asia. There are more small-holder (0.7 ha land/family) farmers. Food availability depends on the small-holders' land productivity, and they still face a great challenge in achieving self-sufficiency in major food products.

Nutrient use rate per ha, fertilizer availability in the market, native nutrient supply ability of the soil and sustainable practice of fertility management practices are important aspects of regulating the nutrient cycle (farm managing level), which is directly linked with food production and hence food availability and food security. The nutrient use rate per ha of Nepal is lowest in South Asia and fertilizer scarcity during rice transplanting is evident and an annually recurring problem. Native nutrient supply capacity is insignificant due to young and immature soils (mostly Entisols and Inceptisols), carbon depletion and soil acidity. For these reasons, the soil production function is has not reached optimum level. Per unit production is not increasing rapidly. Hence, improving these various aspects of farming and managing nutrient supply factors will lead to sustainable intensification of land productivity and help ensure food security.

Soils of Nepal are fragile, young (most of the soils are Entisols and Inceptisols) and less structured. Existence of high intensity rainfall pattern, especially in June-July, caused mostly water erosion accounts for 45.5% in total soil degradation. Various studies conducted in Nepal show that soil loss through surface erosion from agricultural land in the hills varies from 2 tonne/ha/yr to 105 tonne/ha/yr (Gardner and Gerrard, 2003) and even as high as up to 200 t/ha/yr in some degraded rangeland/open land (MoEST, 2006), accounting for top-soil loss (87 t/ha/yr); this is a very serious cause of fertility decline. Such eroded soils raised the soil level in the Terai plains by 35-45 cm per year (Dent, 1984) and deposited more than 300 million tonnes of soil in the Bay of Bengal (Brown 1981). Soil erosion causes a loss of huge amounts of nutrients in the mid, high and foothills of Nepal. Nitrate nitrogen loss was found to be higher in leachate (17.3 – 99.7 kg/ha/yr) than in run-off water (0.7 – 5.6 kg/ha/yr), suggesting that nutrient balance in the overall system is not sustainable (Acharya, 2007). Besides nutrient loss through soil erosion, other factors influence the nutrient cycle in mountainous topography, such as decreasing trend in livestock population (manure is a main source of organic fertilizer in Nepal's livestock-based farming system), shallow soil (<30 cm soil depth) in upper hills, insufficient and haphazard nutrient use rate, inherent acidic soil parent materials in the eastern part of the country and insufficient adoption of soil conservation practices. However, with its rich ecological and biological diversity, Nepal has remarkable potential to address food security. The increasing productivity of food grains, proper utilization of agro-biodiversity, agricultural intensification and mechanization, land utilization, and infrastructure development will help to ensure food security.

Nutrient cycle – a key element for food security

Nutrients constitute a key element for human food production and security. Nutrients are infinite, irreplaceable and cannot be substituted by any other substances. Significant amounts of nutrients are wasted instead of being reused for food production. Karki (2004) reported that reserve soil potassium in intensive farming areas in Nepal is showing a declining trend. Regmi et al. (1998) reported that application of 40 kg/ha potash under rice-rice and wheat rotation cannot maintain the K balance in soils. Based on results gathered over three years from the rice-wheat cropping system in Nepal's lowlands, Pandey et al. (1998) reported that N, P and K were found to be in negative balance after harvest of rice crop, and indicated that use of farmyard manure at 10 tonne/ha is not sufficient to maintain nutrient balance. Disrupted nutrient cycling can pose serious global challenges. There should be nitrogen, phosphorus and potassium efficient food chains for a healthy and sustainable environment.

In the mid-hills of Nepal, the Sustainable Soil Management Program indicated that with the adoption of improved farmyard manure management techniques and systematic collection of cattle urine, farmers gained 18.6 kg of additional nitrogen each year from a matured cow. This represented a significant contribution through on-farm recycling of local resources, as much of this nitrogen would otherwise have been lost through volatilization and leaching. Adoption of these practices contributed to increased productivity, enhanced income and improved food security (FAO, 2015). The vicious cycle of depletion of soil organic matter – decline in crop yield – food insecurity – soil and environmental degradation can be broken by improving soil fertility through enhancement of the soil organic matter pool, which requires use of sustainable agricultural technologies for water and nutrient management including no till farming, compost and mulching, leguminous cover crops, water harvesting, agro forestry and integrated farming system along with judicious use of chemicals. This strategy can break the tyranny of hunger. Nearly one billion people are affected by insufficient food production, a major factor being the shortage of nutrients from fertilizers, i.e. nitrogen and phosphorus. To speed up the progress towards a circular nutrient economy and to integrate nutrient cycling, utilization of nutrient containing waste and side streams effectively, active involvement of all stakeholders (policy makers, commercial fertilizer producers, farmers, scientists in related fields, technology producers, food and feed industry, traders, retailers, consumers) in the nutrient chain is needed.

Nitrogen cycle in food security

Human induced flows of nitrogen and phosphorus are a major component of the earth's biogeochemical cycle (Galloway, 2008). Being a fundamental component of global food and energy security, nitrogen cycle has undergone massive transformation in their structure and functions at various scales. The increased use of N fertilizers has allowed for the production of food that is necessary to support a rapidly growing human population and for increasing per capita overall consumption of meat and milk in particular (Galloway, 2002). Global nitrogen input terms includes fertilizer, manure, biological N_2 fixation, atmospheric N deposition and loss terms include NH_3 volatilization, de-nitrification, nitrate leaching and runoff. The two principal nitrogen nutrients are ammonia (NH_4^+)

and nitrate (NO_3^-) ions. Bhattarai et al. (2000) reported negative balance of nitrogen in vegetable cultivation in the majority of study sites and emphasized use of bacterial fertilizers for maintaining productivity of crops. Gardner et al. (2000) found out that nutrient loss through leachate is a more serious problem than in the sediments. Nitrate-N losses are high during the transition period between the pre monsoon and monsoon seasons in Nepal. Sherchan and Gurung (1992) reported decline of maize productivity over the years because of topsoil erosion, which leads to food insecurity in Nepal.

Food and nutrient security is a critical social complement to ecological boundaries. Previous assessments of planetary boundaries for N only included the conversion of atmospheric N2 to reactive from in fertilizer manufacture (Haber-Bosch process). Nepal has more than 20 fodder tree and shrub species which can fix nitrogen from air; these species are native to the middle mountains of the Nepal Himalaya. Some of them could support mycorrhiza fungi which are able to convert insoluble P into plant available form (FAO, 2015). Crop-livestock production system is the largest cause of alteration of global nitrogen and phosphorus cycles. In addition, the total N and P in animal manures generated by livestock production exceed the global N and P fertilizer use (Bouwman, 2009). Alternative management of livestock production systems shows that combination of intensification, better integration of animal manure in crop production and matching N and P supply to livestock requirement can effectively reduce nutrient flows and increase nutrient cycling in the total agricultural system for food security.

Phosphorus cycle in food security

Phosphorus (P) is a major limiting nutrient in agriculture (Sattari, 2014 and Syers, 2008). As P resources are finite, P is increasingly considered to be a new global sustainability challenge (Cordell, 2014). In the short term, increasing demand for P may lead to rising price of P fertilizer and food, and in the long term, it may lead to depletion of global P reserves (Smil, 2000) that will seriously impact food security, particularly in developing countries. Humans have altered the phosphorus cycle by adding phosphorus for crop production and removing phosphorus through soil management practices, which leads to erosion and leaching. This question is especially relevant as the global issue of P depletion is studied largely from the perspective of P sourcing (i.e. current production and use of phosphate rock) rather than future P requirements, i.e. P is required to feed the world in future (Sattari, 2012). Phosphorus is a non-renewable and finite resource, yet the global agricultural industry depends on phosphorus fertilizers to improve crop yields. It has been estimated that 30-50% of yields can be directly attributed to phosphorus fertilizer and it would take only a small drop in production to cause major problems in the food system.

In cultivated systems, some of the phosphorus taken up by the crop is removed in harvest and then eaten directly by humans or fed to livestock. Because of the leaks from different stages of the nutrient chains, only 20-25 % of the mined P- rock ends up in the human food. The availability and costs of phosphorus is one the key factors that will limit crop yields in the future. As in the case of oil, global phosphorus reserves are also likely to peak, after which production will be significantly reduced (Cordell et al., 2009).

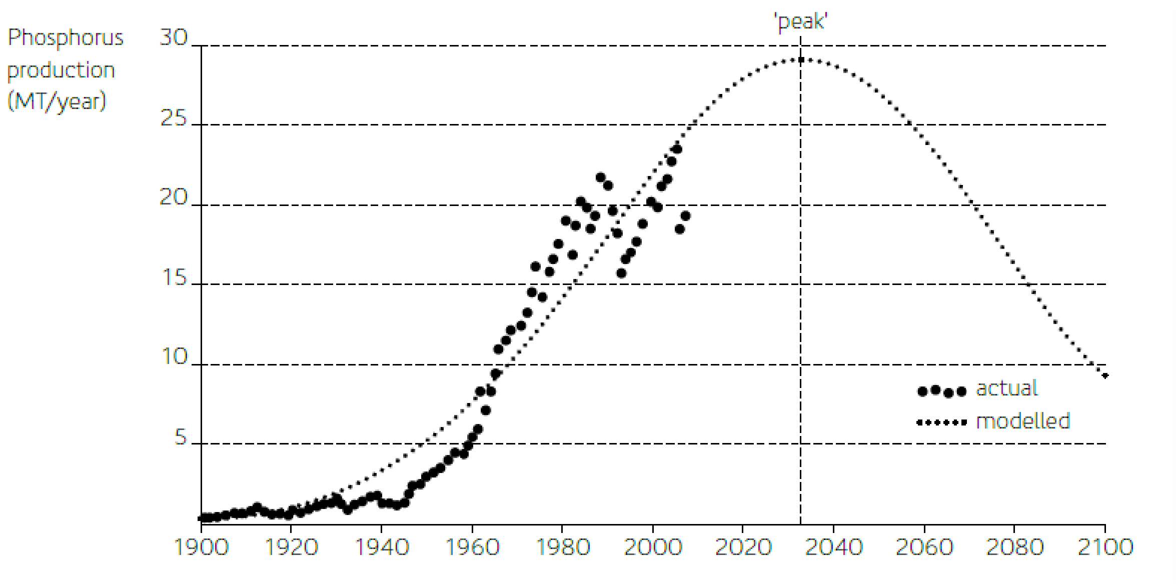

Figure: Indicated peak phosphorus curve (Source: Cordell et al, 2009)

About 15-25% of the phosphorus added to the soil in the form of artificial phosphorus fertilizer and manure can be used by plants in the first year of application. The rest can be stored in the soil in insoluble form, which can be used later when the soluble forms are used up by the crops. This reserve can contribute to P in soil solution and be taken up by crops for many years (Syers, 2008). However, soils differ in their ability to store phosphorus in an insoluble form. Soil cannot hold increasing amounts of phosphate in the insoluble phase without also increasing soil solution phosphate. This increases the risk that the phosphate will be lost via runoff or leaching through soil (Busman, 2009).

Soil carbon sequestration and global food security

Soil organic carbon (SOC) is an extremely valuable natural resource. Irrespective of the climate debate, the SOC stock must be restored, enhanced and improved. Increase in SOC stock increases crop yield even in high input commercial agriculture (Bauer, 1994) but especially in soils where it has been depleted (Johnston, 1986). Soil C sequestration is a strategy to achieve food security through improvement in soil quality. While reducing the rate of enrichment of atmosphere concentration of CO_2, soil C sequestration improves and sustains biomass/agronomic productivity. In the middle mountains of the Nepalese Himalayas, the combination of fodder trees and grasses has proven to be a good management approach. Incorporation of green biomass into soils enhances SOC content and helps in recycling of nutrients, which eventually increases crop productivity and improves food security (FAO, 2015). Depletion of soil organic carbon stock from the root zone has adversely affected soil productivity and environmental quality. An optimum level of SOC stock is needed to hold water and nutrients, decrease risks of erosion and degradation, improve soil structure and provide energy to soil microorganisms. The close link between soil C sequestration and world food security should be given emphasis; it shouldn't be ignored.

Research initiated for improvement of nutrient management practices in Nepal

Soil fertility in the hills is significantly affected by soil erosion. A study conducted under a different management practice on the slopes on the terraces of the mid hills in an area with rainfall 2047 mm has indicated a soil loss of 104 t/ha/yr. When the land at the same site was put under level terraces, the soil loss was brought down to 14.39 tonne/ha/yr (Makey and Joshi, 1991). A study conducted in the high hills and mountain region of Nepal shows that soil erosion is influenced by crops grown under different types of land use. Maize grown as a sole crop resulted in the highest amount of soil loss (2800 kg/ha/yr) but maize when grown with millet reduced soil loss to 480 kg/ha/yr (Ries, 1991). The amount of FYM available to farmers has decreased, reducing the supply of FYM to fertilize the field. Burning of farm residues and FYM used as a fuel has also reduced the availability of organic manure to fertilize the field. This has led to the reduction in the organic matter content of soils in Nepal, especially in the Terai Siwaliks, where it is less than 0.1% in many cases. Soil fertility is decreasing in these areas and if plant nutrients are not replenished adequately from external sources, it is difficult to get satisfactory crop yield (Joshi, 1997).

The strategy on soil fertility at RARS, Lumle has stressed the need for adoption studies on the available technologies of FYM, inorganic fertilizer and green manure, taking into consideration socio-economic factors. Preparation and application of FYM/compost is inefficient, which has reduced the amount of nutrients needed for the crops in the hills of Nepal (LARC, 1997a). In the long-term fertility experiments in Nepal, integrated use of organic and inorganic manure gave higher yield compared to the use of inorganic fertilizer alone in the cropping system involving rice and wheat (Munankarmy, 2000 and Rawal et al., 2017). Efficiency of fertilizer use was improved by applying it in the form of a mudball. A top dressing of 30 kg N per ha in a mudball increased the rice yield from 2544 to 3614 kg/ha over top dressing with ordinary N fertilizer (Sherchan, 1989. Use of indigenous plant materials as green manures like Artemesia vulgaris (Titepati), Adhatoda vasica (Asuro), Eupatorium gladiosa (Banmara), etc. increased the rice yield (Maskey and Bhattarai, 1984) by up to 49%. The results obtained from different trials showed that 30-50 kg N per ha can be supplemented through the application of Sesbania as a green manure (Soil Science Division, 1998). Results on the effect of bacterial biofertilizer in legumes showed that Rhizobium inoculation in legumes increased yield of soybean by 62%, lentil by 25%, blackgram by 49% and peanut by 34% (Bhattarai and Makey, 1998).

To identify the amounts of nutrients required for profitable production of rice and wheat in different soil categories, all soil and plant types must be tested based on the results on which, recommendations will be made for the application of nitrogen, phosphorous, and potassium in the rice-wheat cropping system. This system was initiated in 2016 by the Soil Science Division of Nepal.

Research gaps in enhancing nutrient management in Nepal

- Most of the past research is focused on nitrogen. Very little work has been done on carbon, phosphorus ad potash. Soils of different places have been reported on C, P, K and micronutrients, especially Zn, B, Mo, etc.
- Very few studies have been done on system level nutrient dynamics and balance due to lack of input output data. Farmers lack sufficient knowledge about the right type and dose of fertilizer, resulting in unbalanced use of fertilizer.
- Use of biotechnologies and advanced tools in the areas of soil research.
- Site-specific nutrient management approaches for increasing food at the local levels.
- Rainfall during pre-monsoon and monsoon causes soil and nutrient loss (N, P, and K). Quantification of soil and nutrient losses is limited.
- Limited researches on integrated nutrient management.
- Most farmers follow a cereal-based cropping system, resulting in mining of nutrients. Nutrient balance study is insufficient.
- Most of the research is only focused on soil fertility. A holistic approach (physical, chemical and biological) to soil health has not been adopted yet.
- Poor organic content of soil is observed in most cultivated soils. Farmers are not aware of the importance of recycling crop residue. There are limited studies on residue and organic matter management.
- Limited work on cover crops and soil conservation practices, especially in the hilly region of Nepal.
- Farmers are not practicing green manure by sacrificing other crops; inclusion of grain legume crops for improving soil fertility status is limited.
- Fertilizer recommendations are only made for major crops; system-based recommendations are not available. Recommended dose for many crops hasn't been updated for 40 years.
- Mechanism for linking (coordination) researches on soil is lacking.
- Research on farm conservation, sloping agricultural land technology and agro forestry practices for soil conservation is lacking.

Conclusion

The studies discussed in this paper highlight the role of nutrient cycling in food security. The paper also provides evidence that optimization of plant nutrients has a role in ensuring food security because by maximizing the efficiency of the production inputs, unit produce cost can be reduced and farm produce can be made more competitive. At the same time, national farm policies may be needed to ensure that highly productive agricultural soils are replenished with adequate nutrients in order to sustain their productivity. All these factors will contribute towards increasing agricultural production and ensuring food security. Finally, the studies also underscore the need to raise stakeholders' awareness about the urgent need to recover and use nutrients from wastes and to utilize nutrients more efficiently in the food production-consumption –waste cycling chain.

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Soil fertility management for sustained crop production in Gilgit-Baltistan: the northernmost mountainous region of Pakistan

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Abstract

The Gilgit-Baltistan (GB) region, located amongst the three mightiest mountain ranges of the world (the Himalaya, Karakoram and Hindu Kush), is one of the major deciduous fruit producing areas of Pakistan. The most common cultivated land in GB are on alluvial fans created from the sporadic mass movement of soil, most typically in the form of mud flow, river terraces and colluvial deposits. Most of the soils in Gilgit-Baltistan are deficient in organic matter content, which causes low productivity of major crops. Large numbers of high yielding fruit varieties of different species have been introduced in the region during the last two decades but the farmers could not get expected benefits from these varieties due to lack of information on the fertility status of their fields and orchards and nutrient requirement of these varieties. In this context, Pakistan Agricultural Research Council (PARC) is carrying out research and development on fertility management and improvement of agricultural productivity in arid and semi-arid areas. This study evaluates the physico-chemical characteristics and fertility status of the Gilgit Baltistan soils to formulate proper recommendations for maximizing agricultural productivity through proper management of soil fertility. Important physico-chemical properties, such as soil texture, organic matter, EC, pH, N, P, K and micronutrients (Cu^{2+}, Fe^{2+}, Zn^{2+}) were determined.

Introduction

Gilgit-Baltistan is famous for potato and deciduous fruits like apple, apricot, almond, cherries, plum, and peaches, etc. but the fruit yield and quality is not up to the mark due to poor nutritional management and nutrient deficiencies as the soil fertility is either inherently poor or is degraded due to poor management over a long period of time. Disorders and abnormalities are caused by deficiency or excess of nutrients in soil and water. The concept of balanced fertilization has not yet been addressed in the area. Balanced fertilization is very important for increasing the yield, improving the quality and minimizing the risk of nutrition related diseases. Most farmers apply urea in their fields and some farmers also use phosphorus in the form of nitrophos fertilizer. This practice has been carried out for decades, which has caused deficiency of other nutrients and affected yields drastically. Appropriate and adequate soil management practices like levelling of land, cultural practices, balanced fertilizer application and mulching etc. can help to cut down nutrient losses and to improve fertilizer use efficiency.

MARC carried out research on proper nutrient management techniques and integrated nutrient management for improving the productivity of crops and fertilizer use efficiency. They investigated the nature, extent and severity of micronutrients to determine micronutrient fertilizer requirement for various cropping systems. MARC's research aimed to determine the nature of nutrient disorders in fruit orchards and to develop soil fertility management practices for optimum fruit yield and to improve soil fertility through the addition of organic matter, by cultivating legume crops on marginal lands and through crop rotation. It is necessary to develop appropriate technologies for the soils of Gilgit Baltistan. For this purpose, experiments on various dimensions of fertilizer and integrated nutrition management strategies were conducted at different locations of Gilgit- Baltistan during the last five years. The information generated was shared with the farmers to help increase their production, to save their resources (as the majority of farmers are poor and depend mostly on agriculture), and to enable them to use the fertilizers and other inputs on a sustainable basis so as to increase their yield and income.

The area has a very fragile ecosystem and faces the constant threat of soil degradation, soil erosion and depletion of resource base. To address the fertility issues of low yield and fertility problems of fruit orchards and crops, research was initiated on fertility evaluation of various sites. The aim was to get a clear picture of physico-chemical properties as well as the fertility status of various sites besides conducting filed experiments at the research station as well as on farmers' fields.

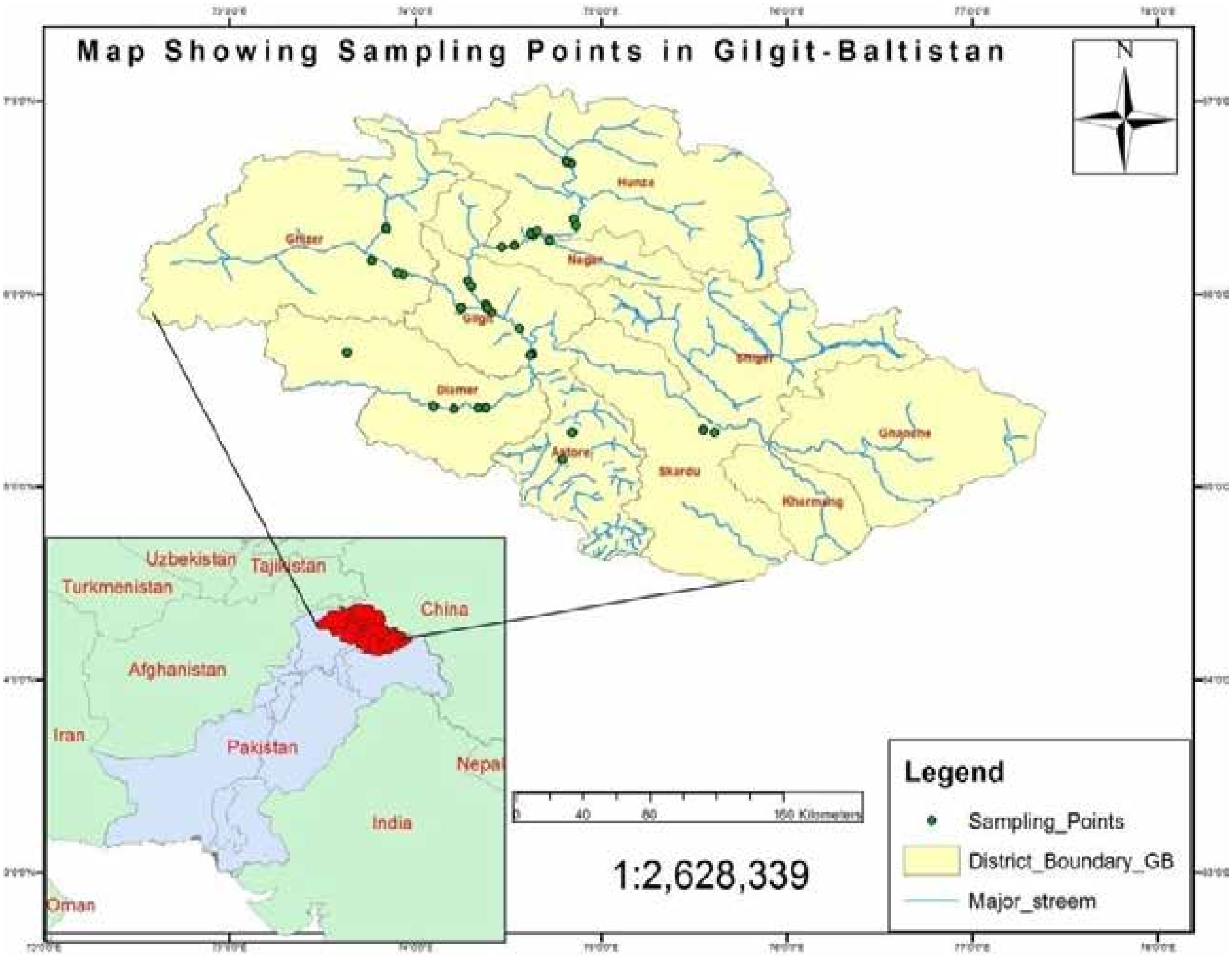
The present paper highlights the fertility statuses of GB soils, and makes recommendations for fertility management of orchards and filed crops.

Methodology

The Mountain Agricultural Research Centre (MARC) conducted various studies on fertility management and nutrient status of plants and soil. Nutrient analyses of various field sites and fruits orchards were carried out to identify nutritional problems, to measure tree response to applied fertilizers and to detect low level deficiencies of essential nutrients in plant and soil samples. These analyses were carried out in the soil analysis lab of MARC. Samples were collected from different sites at various altitudes and places. Quadrates of the village sites from where the samples were collected were also noted. Filed experiments were conducted at farmers; orchards and analysis was carried out in the soil and plant analysis laboratory of MARC.

Evaluation of soil fertility and assessment of physico-chemical properties of soil

Soil fertility evaluation and assessment of physico-chemical properties of soil samples were carried out and about three hundred and fifty soil samples of various sites were analyzed for soil properties and nutrient status.



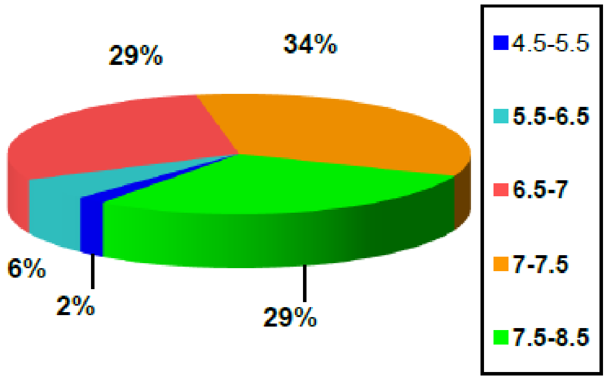
Soil samples were prepared for analysis at the soil analysis laboratory of MARC. The collected samples were dried and then sieved using a 2mm mesh and kept for analysis. The soil properties like pH, Ec, organic matter content and soil texture were determined. Statuses of soil macro nutrients such as Nitrogen, Phosphorus, Potash, and of micronutrients such as Iron, Copper and Zinc from different orchards were tested and the data samples were summarized in the following charts and diagrams.

The soil pH and Ec was normal in most of the samples. Majority of the tested soil samples were light textured. Soil organic matter was also low in most of the soil samples.

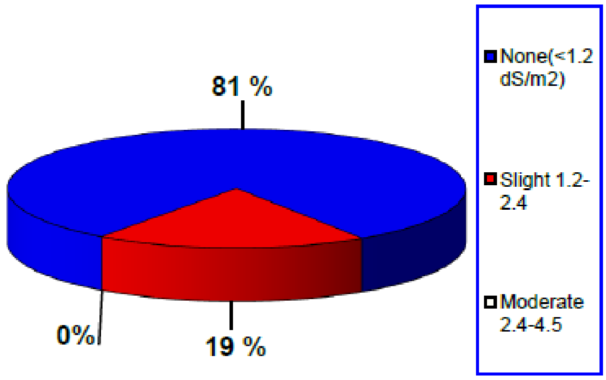
Among macro nutrients all the three major nutrients i.e. Nitrogen, Potash and Phosphorus were low. Among micronutrient Iron and Copper were adequate in majority of the samples while Zinc was low in most of the soil samples.

Physicochemical properties of samples

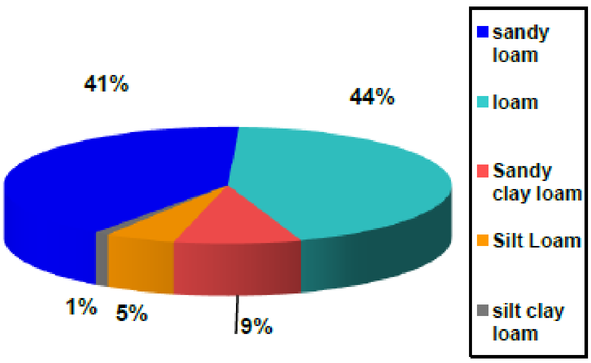
PH



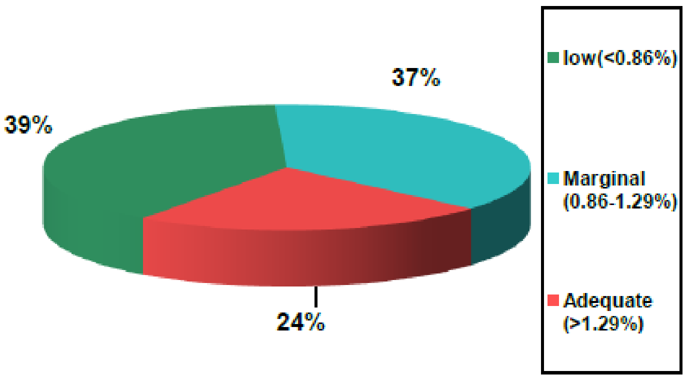
Ec



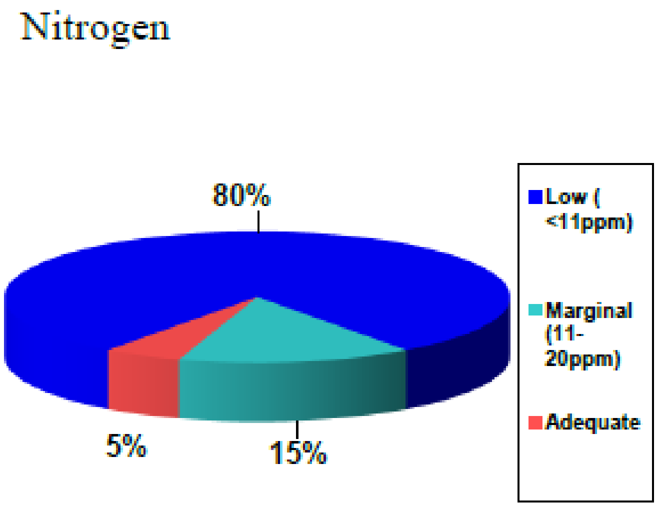
Texture

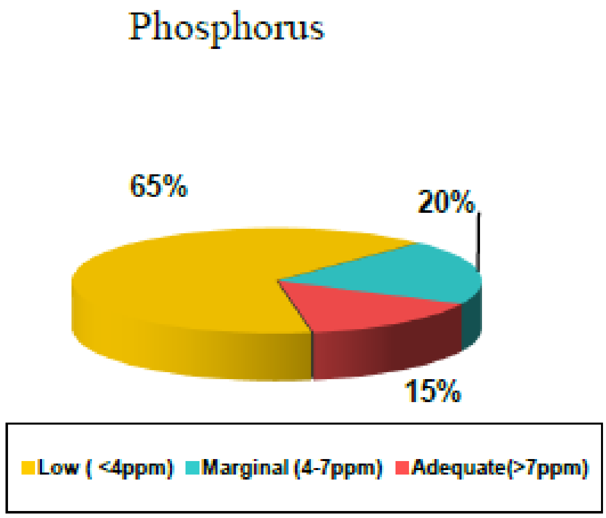


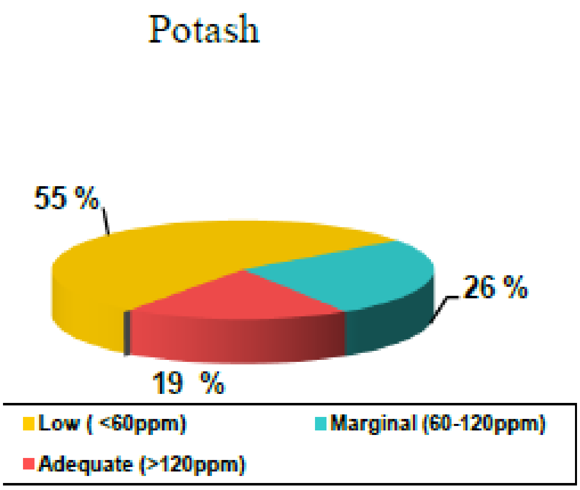
OM

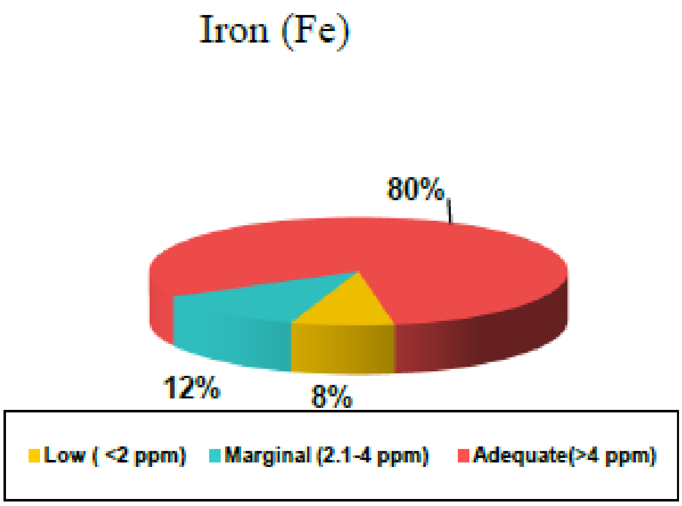


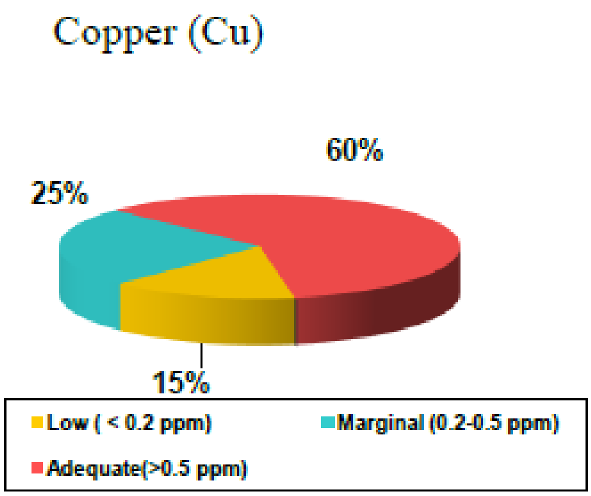
Soil nutrient status of different sites

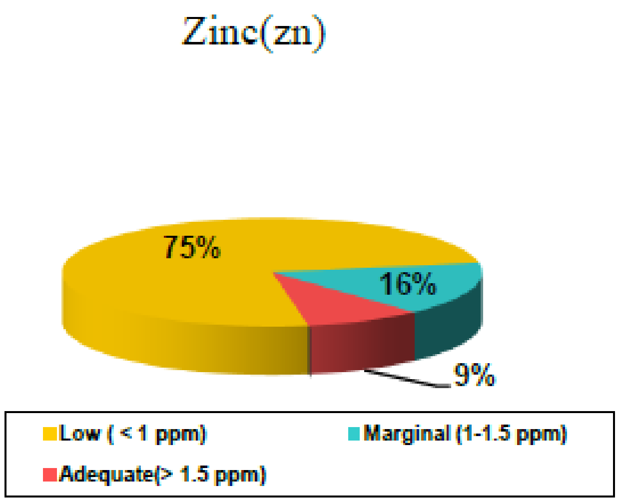












Recommendations

Crops

Based on the soil analysis findings and field experiments, crop rotation with legumes, composting and green manuring, proper N, P, K (90-120 kg ha^{-1} N, 60-90 kg ha^{-1} P_2O^5, 40-60 kg ha^{-1} K_2O) fertilizer along with low doses of Zn addition is recommended for sustainable productivity of GB soils.

Fruit trees

Besides the nutrient analysis, the fertilizer trials at different locations showed that all the fruit species responded positively to the applied nutrients at all locations. To obtain higher and economical yields, the following levels of Nitrogen, Phosphorus and Potash were recommended for each species.

Apricot: Based on the experiment, the most appropriate levels of Nitrogen, Phosphorous and Potash seem to be 800 g/plant N, 200 g/plant P2O5 and 200 g/plant Potash along with 5 kg/plant well rotten FYM for obtaining higher and economical yields. Nitrogen fertilizers may be applied in two batches.

Almond: For better and economical yields of almond, the most suitable doses of Nitrogen, Phosphorus and Potash are 800 g/plant N, 300 g/plant P2O5 and 400 g/plant K2O respectively besides application of two tonnes of FYM per hectare. The nitrogen fertilizers may be applied in three batches i.e. before flowering, after fruit set, and in mid season stage.

Cherry: Cherry is the most early maturing fruit crop. Two batches of nitrogen fertilizer along with basal doses of Phosphorus and Potash are required for better yield along with application of FYM. Improved cultural and management practices are required even after harvesting the fruits to obtain good yields in the following year. NPK may be applied at 400, 200 and 200 g per plant.

Apple: Apple is among the late maturing fruits. Its fruit ripening season is the longest. As per experimental work and data, the most suitable level of Nitrogen, Phosphorus and Potash were 800 g/plant N, 200 g/plant Phosphorus and 300 g/plant Potash respectively along with 2 tonnes per hectare of well rotten FYM.

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Intensive agricultural practices in Nepalese hills contributing to soil quality decline and emissions increase

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Abstract

In Nepal, agricultural intensification is manifested in the increased number of crops and increased use of chemical fertilizers and is seen as an option for increasing production. Mid-hill farmers have shifted from the subsistence-based farming system to intensified farming system and intensification has been increasingly adopted over the past few decades. The increase in use of di-ammonium phosphate (DAP), potash and urea, has led to a decrease in farmyard manure application. The direct and indirect effect of excessive amounts of nitrogen fertilizer is the main driver of acidification, in combination with enhanced extraction of base cations through crop uptake and removal with harvests. N2O emissions from intensified farming are higher both in Khet and Bari than in adjacent traditional crop production. Most of the N2O emissions took place during the rainy season. Greater N2O emissions during rainy season were associated with higher soil moisture content that enhances microbial activity. The microbial activities are further enhanced by N inputs leading to increase in the denitrification process.

Background

South Asian countries have a number of common features such as high human-to-land ratio, a high share of agriculture in gross domestic product (GDP), weak infrastructure and a high proportion of population living below the poverty line. The average per capita cropland (ha/person) for the region was 0.38 in 1960, and is projected to be 0.10 in 2025 and 0.093 in 2050 (Lal, 2011). There is a stated need to intensify agriculture rather than extending cultivation to increasingly marginal lands.

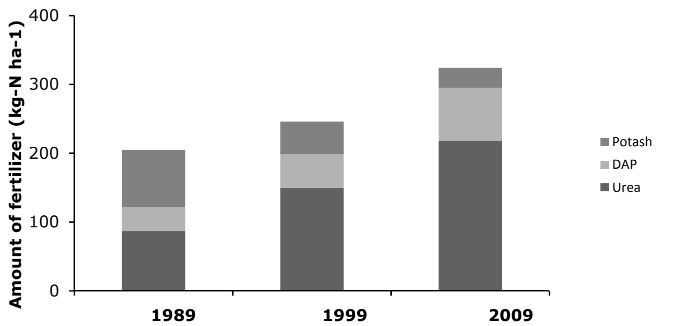
The average landholding of 0.76 ha in 1989 was reduced to 0.63 ha in 2009 (Raut et al., 2011). Therefore, agricultural intensification is seen as an option for increasing production. Mid-hill farmers have shifted from the subsistence-based farming system to intensified farming system and intensification has been increasingly adopted over the past few decades. Market-oriented production is one of the principal factors shaping land-use dynamics in the middle-hills of Nepal (Brown and Shrestha, 2000, Pokhrel and Thapa, 2006).

Agricultural intensification is manifested in the increased number of crops and increased use of chemical fertilizers. In a recent study that looked at the past, present and future direction of farmers' practices in the Ansikhola watershed of Nepal (Raut et al., 2011), we showed that the amount of Nitrogen fertilizer application has increased dramatically and that the history of intensification exceeds 30 years. Input-intensive cultivation in various agricultural sub-sectors has led to environmental challenges in Asia. Many of the current agricultural practices increase pollution, soil degradation, and pose major threats to agricultural production and human health in the long run.

Implications of inorganic fertilizer use on soil quality

The major fertilizers used in Nepal are urea, di-ammonium phosphate (DAP) and potash. The average amount of urea (kg-N per ha) used significantly increased over the last 30 years. Likewise, the trend of DAP application was also significantly increasing over the past few decades. In contrast, farmyard manure application has been decreasing. The direct and indirect effect of excessive amounts of nitrogen fertilizer is the main driver in acidification, in combination with enhanced extraction of base cations through crop uptake and removal with harvests (Raut et al., 2012). In their study, they have conducted a pairwise comparison of plots with a history of intensified cultivation, and adjacent plots with a more traditional low input farming practice shows convincingly that the intensification (higher N inputs, three versus two crops per year) has lowered the pH of the soil

Figure 1: Comparisons of annual inputs of fertilizers during 1989, 1999 and 2009 in irrigated land



Source: Raut et al., (2011)

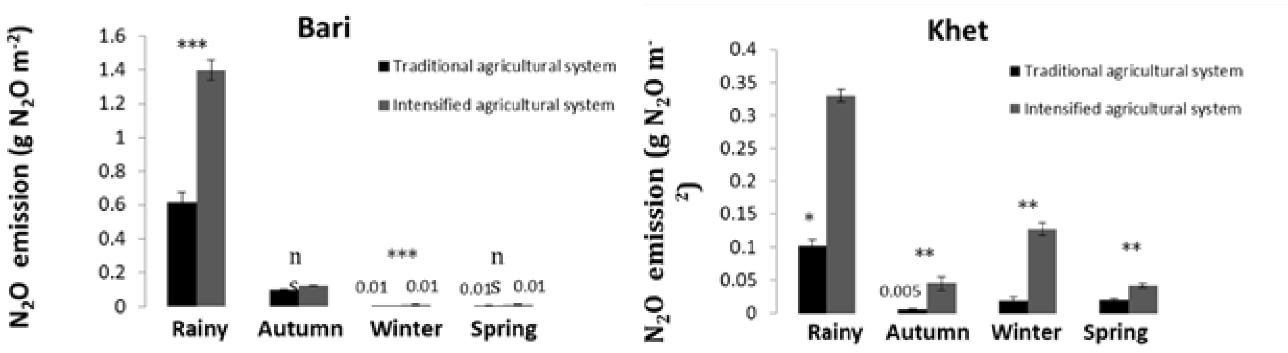
substantially. A similar trend of agricultural soils getting acidic was also reported in Chinese agriculture (Guo et al., 2010). Studies showed that deficiency of micronutrients, especially boron and molybdenum, is increasing in different ecological belts at varying intensities (Karki et al., 2004). In the hills where vegetables are being grown during off-season and normal season, boron and molybdenum are deficient.

Agricultural intensification promotes a minimum of three crops per year, which means that the frequency of soil tillage has also increased. In hilly areas where land is tilled more frequently, soil loss from topsoil leads to serious environmental degradation. It has been well reported that more than 50 percent of soil loss occurred during the early monsoon period (Shrestha et al., 2005), and that led to decrease in crop productivity.

Intensified crop production on greenhouse gas emission

Intensified crop production has been found to acidify soils and increase their apparent propensity to emit N_2O as measured by the $N_2O/(N_2+N_2O)$ product ratio of denitrification (Raut et al., 2012). Measurements of N_2O emissions from intensified and adjacent traditional crop production fields were conducted; these were fields on which intensified production system had been practiced for the last 20 years. The measurements were carried out every one to two weeks over a period of 12 months covering two to three cropping periods. On the sites with periodically flooded soils (*Khet land*), the cumulated emissions for intensified crop production and traditional crop production were 15.41 and 7.23 kg N_2O/ha, respectively. On the sites with permanently drained soils (*Bari land*), the cumulated emissions were 5.43 and 1.46 kg N_2O/ha for intensified and traditional crop production. Most of the N_2O emission took place during the rainy season. Greater N_2O emissions during rainy season were associated with higher soil moisture content that enhances microbial activity. Microbial activities are further enhanced by N inputs leading to increase in the denitrofication process (Raut et al., 2015).

Figure 2: Seasonal accumulated fluxes of N_2O (a) *Bari* land and (b) *Khet* land



*, ** and *** are significantly different at p<0.05, 0.01 and 0.001 respectively.
Source: Raut et al. (2015).

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Theme: Soil erosion and degradation

Himalayan environment has already deteriorated to an alarming extent

- Soil degradation in the HKH region is one of the major threats to humanity as this diverse mountain region provides ecosystem services to one fifth of the world's population. Degradation of mountain soil not only reduces food availability for a growing population, but also hinders ongoing efforts to mitigate environmental problems in this region.
- Over-exploitation and inappropriate practices due to unabated population growth, industrialization and urbanization that prioritizes immediate gains in order to meet the growing demands without adopting a long-term perspective, have resulted in soil degradation by various processes, which are directly/indirectly associated with environmental problems such as greenhouse gases, global warming and others.

Soil degradation and challenges in land reclamation in the Indian Himalayan region

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Abstract

Land degradation is prevalent in many forms throughout India. In 2016, ISRO-Desertification and Land Degradation Atlas of India reported 90.4 Mha degraded area in the country. The major forms of soil degradation are water erosion, wind erosion, water logging/flooding, salinity/alkalinity, soil acidity and complex problem. The steep slopes, fragile geology, and intense storms trigger soil erosion in the Himalayas. Erosion rates are high for the Shiwalik hills (~80 ton ha−1 year−1) and shifting cultivation areas (~40 ton ha−1 year−1). The extent of water erosion is more severe in the North Eastern Himalayan (NEH) region (22.3% of TGA) than in the North West Himalayan (NWH) region (12.6% of TGA). Moreover, excessive erosion is also leading to decline in soil fertility. The extent of soil and nutrient transfer by water erosion in the NEH region was estimated at ~601 Mt of soil, and 685.8, 99.8, 511.1, 22.6, 14.0, 57.1, and 43.0 thousand tonnes of N, P, K, Mn, Zn, Ca, and Mg, respectively. Similarly, shifting cultivation coupled with excessive deforestation have resulted in tremendous soil loss (>200 tonne ha−1 year−1) in some areas with poor soil physical conditions. The problem is likely to be increased by the effects of climate change.

It is important to adopt a multi-disciplinary approach combining theoretical and applied knowledge in all the relevant domains to understand the complex human environment systems. Afforestation and reforestation should be carried out; standard techniques for improving our pasture lands should be implemented and grazing in forest areas should be minimized because cattle damage young seedlings and saplings that might be necessary for regeneration, and their hooves increase soil compactness, thereby increasing soil erosion and runoff; removal and burning of forest litter should be avoided; acidic, saline and sodic soils should be reclaimed with timely availability of ameliorating materials; planting of bio-fuel plants should be encouraged; mining should be carried out on degraded land and it should later be reclaimed with better land use. The strategies to reduce soil degradation should be institutionalized, financially coherent and socially acceptable, as well as meaningful, consistent and coherent across all the sectors and related actors for the long-term sustainability of this unique ecosystem.

Introduction

Soil degradation is an outcome of depletive human activities and their interaction with the natural environment. Soil degradation is responsible for the decline of soil quality. Over-exploitation and inappropriate practices due to unabated population growth, industrialization and urbanization that prioritizes immediate gains in order to meet the growing demands without adopting a long-term perspective, have resulted in soil degradation by various processes at an alarming rate (Yadav, 2002) and that is directly/indirectly associated with environmental pollution e.g., green house gases, global warming, acid rains, etc. India covers a geographical area of 328.7 million hectares (Mha), out of which 304.9 Mha comprise the reporting area with 264.5 Mha being used for agriculture, forestry, pasture and other biomass production. Soil degradation in India is estimated to be occurring on 147 Mha of land (NBSS & LUP, 2004) out of which >94 Mha is degraded by water erosion. India suffers from deleterious effects of soil erosion with an average soil erosion rate of ~16.0 tonne ha^{-1} $year^{-1}$, resulting in an annual total soil loss of 5.33 billion tonnes throughout the country (Pandey et al., 2007). Nearly 29 percent of the total eroded soil is permanently lost to the sea, while 61 percent is simply transferred from one place to another and the remaining 10 percent is deposited in reservoirs.

Land degradation is prevalent in many forms throughout the country. In most cases, the problem occurs as a combination of various forms. In the absence of comprehensive and periodic scientific surveys, estimates have been made on the basis of localized surveys and studies. The National Bureau of Soil Survey and Land Use Planning (NBSSandLUP) Nagpur, of ICAR reported in 2005 that an area covering 146.82 Mha is suffering from various kinds of land degradation. It included water erosion 93.68 Mha, wind erosion 9.48 Mha, water logging/ flooding 14.30 Mha, salinity/alkalinity 5.94 Mha, soil acidity 16.04 Mha and complex problem 7.38 Mha. However, as per recent estimates from 2016, ISRO-Desertification and Land Degradation Atlas of India reported 90.4 Mha degraded area in the country.

Land degradation is the temporary or permanent lowering of the productive capacity of land (UNEP, 1992). It thus covers various forms of soil degradation, adverse human impacts on water resources, deforestation, and lowering of the productive capacity of rangelands. Soil erosion by water and wind, deterioration of soil physical, chemical and biological properties, water logging, and the build-up of toxicities, particularly salts, in the soil are a major concern. Since soil productivity is intimately connected to water availability, lowering of the groundwater table is also a concern. FAO considers deforestation to be a primarily cause of soil degradation, particularly erosion.

Extent of soil degradation in India

Soil degradation is caused by excessive pressure put on land to meet the demand of the growing population for food and fodder. Land degradation status and severity are presented in Tables 1-2.

Table 1: **Land degradation status in physiographic regions**

Physiographic Region	Total Area in Mha	Land Degradation Type (area (Mha)				
		Water erosion	Wind erosion	Physical deterioration	Chemical deterioration	**Total**
Himalayan Region	48.30 (14.70)	16.8	–	0.45	2.80	**20.05**
The Great Plain	85.90 (26.10)	24.4	10.8	5.48	3.58	**44.26**
Peninsular Upland	141.40 (43.00)	79.36	0.70	1.00	2.96	**84.02**
Coastal Region	53.10 (16.20)	20.77	–	5.70	3.90	**30.37**
Total	**328.70**	**141.33**	**11.50**	**12.63**	**13.24**	**182.03**

Source: Saxena and Pofali (1999)

Various human activities like large-scale irrigation canals, construction of roads, mining and deforestation lead to accelerated soil degradation through salinization, flooding, erosion. etc. Forest fire, overgrazing, burning of grasslands also lead to soil degradation.

Table 2: **Severity of soil degradation and its extent (Mha)**

Degradation type	Severity of degradation				Total area
	Low	Medium	High	Very high	
1. Water Erosion (W)	**5.0**	**24.3**	**107.2**	**12.4**	**148.9**
1. Wind Erosion (E)					
Loss of top soil (Et)	-	-	6.2	-	**6.2**
Loss of top soil or terrain deformation (Et/Ed)	-	-	4.6	-	**4.6**
Loss of soil due to terrain deformation or due to over blowing (Ed/Eo)	-	-	-	2.7	**2.7**
2. Chemical Deterioration(C)					
Salinization (Cs)	2.8	2.0	5.3	-	**10.1**
Loss of nutrients (Cn)	-	-	3.7	-	**3.7**
3. Physical Deterioration (P)					
Water logging (Pw)	6.4	5.2	-	-	**11.6**
Total area	**14.2**	**33.2**	**124.3**	**16.1**	**187.7**

Source: Sehgal and Abrol (1994)

Himalayan scenario

The Himalaya is the greatest and the youngest of all mountain systems. It extends about 2500 km from northeast to southeast and its width ranges from 250 to 300 km. The Himalaya consists of four longitudinal belts separated by faults. Its geological and topographical characters are strikingly different. To the north of the plains is the Siwalik mountain belt whose width ranges from 10 to 15 km and altitude exceeds 900 m. The next mountain belt is the lesser Himalaya; its width ranges from 60 km to 80 km and its average height is 3,000 m. The third belt is the Greater Himalaya comprising of high snow-capped peaks. This zone consists of the lower alpine zone with elevations up to 4,800 m and the upper snow-bound zone usually above 5,000 m.

The Trans-Himalayan zone, with a width of 40 km, consists of valleys and rivers and rises behind the Great Himalaya (Valdiya, 1980). It is the source of the mighty Ganges, the Indus, the Brahmaputra, and the Yangtze, and home to ten river basins of South Asia, Central Asia and China. The combined drainage basin of the Ganges, the Indus and the Brahmaputra is a source of water for about 600 million people in the mountains as well in the plains of India. Almost the entire population of all countries across the Pan-Himalayan region is dependent upon the Himalaya as the source of livelihood and ecosystem services. A large proportion of the population in the region lives in abject poverty with poor infrastructure and standard of living.

The Indian Himalaya occupies an area of 53.7 Mha, constituting 16.4 percent of the total geographical area (TGA) of the country. It consists of two distinct sub regions viz. the eastern Himalayan region or northeastern hills (NEH) and the western Himalayan region or northwestern hills (NWH). Annual rainfall in the NEH region is high (2,800–12,000 mm) compared to the NWH region (350–3,000 mm). Other than soil erosion by water, mass erosion, land slide/land slips, etc. cause soil loss. Human-induced intensification of land sliding has been caused by vegetation clearing, construction of roads and buildings, mining, and hydropower projects.

Types of land degradation assessed and problems in the Himalayan region

Land that is undergoing soil degradation in India has been classified into hilly and mountainous areas, Trans- and upper Indo-Gangetic Plains (IGP), middle and lower Indo-Gangetic Plains and coastal areas, dryland and desert areas, southern peninsular India and central India. The Himalayan region falls under hilly and mountainous areas. The area under open forests with canopy <40% is greater in the Himalayan region (~3.1% of TGA) than the national average (2.5% of TGA). Also, the area affected by barren and stony wastelands is greater in the Himalayan region (~6.7% of TGA) than the national average (~1.8% of TGA).

Burning of vegetation by forest fire and decline in biodiversity are serious issues in the NEH region. Climate change has affected the Himalayan forests by changing the forest community structure. The Himalaya also suffers from the problem of overgrazing. For instance, in Uttaranchal Himalaya, incidence of overgrazing is 2.4 to 4.5 times higher than the carrying capacity of forest (Singh and Saxena, 1980). The annual depletion of forest amounts to 3.76 million m3 per year, i.e., at the rate of 5.8% per year (Shah, 1985). Maximum land degradation occurs in the civil forest areas because of uncontrolled and unscientific anthropogenic activities. Land degradation has been grouped into six classes: water erosion, wind erosion, soil fertility decline, salinization, waterlogging, and lowering of the water table.

Water erosion covers all forms of soil erosion by water, including sheet and rill erosion and gullying. Human-induced intensification of landsliding, caused by vegetation clearance, road construction, etc., is also included. Water erosion covers all forms of soil erosion by water, including sheet and rill erosion and gullying. The Himalayas have steep slopes, fragile geology, and intense storms, all of which trigger soil erosion. Erosion rates are high for the Shiwalik hills (~80 tonne ha^{-1} $year^{-1}$) and shifting cultivation areas (~40 tonne ha^{-1} $year^{-1}$). Nearly 39 percent of the area has a potential erosion rate of >40 tonne ha^{-1} $year^{-1}$. The extent of water erosion is more severe in the NEH region (22.3% of TGA) than in the NWH region (12.6% of TGA) (Table 3).

Table 3: **Extent of land degradation area (%) in various states of the Indian Himalaya**

Regions/All India	Degradation Classes										
	1	2	3	4	5	6	7	8	9	10	11
NWH	9.13	2.72	0.22	0.76	0.54	0.95	0.11	11.55	13.68	41.74	18.69
Total for NEH	8.77	5.44	4.32	8.51	25.04	5.54	0.94	1.02	4.33	0.64	35.71
Total for the Himalaya	8.96	3.97	2.11	4.34	11.84	3.06	0.49	6.69	9.37	22.79	26.54
All India total	**22.3**	**2.8**	**1.6**	**1.74**	**2.2**	**2.5**	**0.3**	**1.8**	**1.6**	**3.9**	**59.4**

Degradation Classes	Description	Degradation Classes	Description
1	Exclusively water erosion (>10 tonne ha−1)	7	Water logged and marshy
2	Water erosion under open forest (<40% canopy)	8	Barren/stony waste
3	Exclusively acid soils (pH < 5.5) glacial area	9	Snow covered and glacial area
4	Acid soils under water erosion	10	Area not surveyed
5	Acid soils under open forest	11	Others
6	Exclusively open forest		

NWH = Northwest hills; NEH = Northeastern hills
Source: CSWCRandTI Vision (2011)

Wind erosion refers to loss of soil by wind, primarily occurring in hot and cold dry regions. Wind erosion is a serious problem in arid and semi arid regions. In India wind erosion is moderate to severe in arid and semi-arid areas of the north-west that cover an area of 28, 600 km^2 of which 68% is covered by sand dunes and sandy plains (Gupta, 1990). Wind erosion is costly for the economy, human health and the environment: it can lead to soil loss, high cleaning bills, absenteeism, transport delays, sand-blasted crops and retail losses.

Soil fertility decline refers to the deterioration of soil physical, chemical and biological properties. Whilst decline in fertility is indeed a major effect of erosion, the term is used here to cover effects of processes other than erosion. The main processes involved are:

- Lowering of soil organic matter, with associated decline in soil biological activity;
- Degradation of soil physical properties (structure, aeration, water holding capacity), as brought about by reduced organic matter;
- Adverse changes in soil nutrient resources, including reduction in availability of the major nutrients (nitrogen, phosphorus, potassium), onset of micronutrient deficiencies, and development of nutrient imbalances;
- Build up of toxicities, primarily acidification through incorrect fertilizer use.

Whilst decline in fertility is indeed a major consequence of erosion in the Indian Himalayan states, processes other than erosion include: (i) declining soil organic matter (SOM) associated with declining soil biological activity; (ii) degradation of soil physical properties (structure, aeration, water holding capacity), as brought about by declining SOM; and (iii) reduction in the availability of major nutrients and onset of micronutrient deficiencies. The extent of soil and nutrient transfer by water erosion causing environmental degradation in the NEH region was estimated at ~601 Mt of soil, and 685.8, 99.8, 511.1, 22.6, 14.0, 57.1, and 43.0 thousand tonnes of N, P, K, Mn, Zn, Ca, and Mg, respectively. Soils are deficient in N since it is lost through leaching (in levelled terraces) and runoff. Due to intensive cultivation of cereal-based cropping systems [e.g., rice-maize (*Zea mays* L.)–wheat] without proper application of a balanced dose of fertilizer, Zn deficiency occasionally appears. Soils are typically deficient in S, B and Mo in areas of the NWH region. Toxicities of Al and Mn are also prevalent in the NEH region. The account of nutrient addition and removal in the north-western hills of India is given in Table 4.

Table 4: **Nutrient addition and removal in the north-western Himalayan region of India**

States	Fertilizer Use ($kg\ ha^{-1}\ year^{-1}$)	Nutrient Removal ($kg\ ha^{-1}\ year^{-1}$)	Gap ($kg\ ha^{-1}\ year^{-1}$)
Uttaranchal	8	70	62
Himachal Pradesh	35	130	95
Jammu and Kashmir	40	147	107

Source: Ghosh et al. (2012)

Water logging is the lowering of land productivity through the rise in groundwater close to the soil surface. Also included under this heading is the severe form, termed 'ponding', where the water table rises above the surface. Water logging is linked with salinization, both being brought about by incorrect irrigation management.

Salinization is used in its broad sense, to refer to all types of soil degradation brought about by the increase of salts in the soil. It thus covers salinization in its strict sense, the build up of free salts; and codification (also called alkalization), and the development of dominance of the exchange complex by sodium. As human-induced processes, these occur mainly through incorrect planning and management of irrigation schemes. Also covered is saline intrusion, the incursion of sea water into coastal soils arising from over-abstraction of groundwater.

Lowering of the **water table** is a self-explanatory form of land degradation, brought about through tube well pumping of groundwater for irrigation exceeding the natural recharge capacity. This occurs in areas of non-saline ('sweet') groundwater. Pumping for urban and industrial use is a further cause.

Shifting cultivation, also known as **Jhum cultivation**, is the most traditional and dominant land use system in the NEH. On average, 3.9 Mha of land is under shifting cultivation every year (CSWCRTI, 2011). The system involves cultivation of crops on steep slopes. Land is cleared by cutting the forest or bush to stump level, leaving cut materials to dry and eventually burn to prepare the land for sowing before the onset of rains. Excessive deforestation coupled with shifting cultivation practices have resulted in tremendous soil loss (>200 ton ha^{-1} $year^{-1}$) in some areas with poor soil physical conditions. Saha et al. (2012) reported highest soil loss (30–170 ton ha^{-1} $year^{-1}$) from shifting cultivation, which is followed by conventional-tillage agriculture (5–68 ton $ha^{-1}year^{-1}$).

Potential effects of global climatic change

Significant global warming phenomena have already been observed and are projected to continue (IPCC, 2007). It is possible that this may lead to modifications to the general atmospheric circulation with consequent changes in rainfall. Warming is expected to lead to changes in climate variables such as precipitation, temperature, wind speed, and solar radiation. For instance, the numbers of rainy days are likely to decrease along with a marginal increase of 7-10 percent in annual rainfall over the sub-continent by the year 2080, leading to high-intensity storms. While monsoon rainfall over the country may increase by 10-15 percent, winter rainfall is expected to decrease by 5-25 percent, and seasonal variability would be further compounded (CSWCRTI, 2011)

These changes in climate have the potential to affect soil erosion in a variety of ways. Direct impacts on soil erosion include changes in the erosive power of rainfall due to changes in rainfall amounts and intensities (Nearing, 2001). Shiono et al. (2013) compared the rainfall erosivity, R-factor of farmland areas in a near-term period (2031–2050) and a future period (2081–2100) with a recent period (1981–2000) in Japan.

Challenges in land reclamation in the Indian Himalayan region

A country like India cannot afford to allow more than 50 percent of its land area to remain unproductive. However, 50 percent of the total land area occurs as wastelands scattered throughout the length and breadth of the country. Problems of the 12 Himalayan states of the Indian Himalayan Region (IHR) vary from state to state due to variable climate and rainfall pattern (extreme arid to extreme wet), different ecosystems (ranging from cold deserts to sub-tropical evergreen rainforests, diversity of cultures and indigenous communities, and different farming practices – from subsistence farming to shifting cultivation. Strategies and plans of action therefore i) need to be localized and ii) specific to the mountainous/hilly region and iii) specific to each of these states/regions.

Strategies to reduce soil degradation

- Soil conservation planning should be formulated on the basis of the severity of degradation due to water, wind, anthropogenic activities, etc.
- Afforestation and reforestation activities should be adopted to protect agricultural lands from further deterioration.
- Afforestation of degraded and wastelands should be given priority. It will not only improve soil fertility but will also be very helpful in sequestration of carbon in the soil.
- Grazing in forest areas is perhaps the severest factor responsible for increasing biotic pressure on the Himalayan forests. Standard techniques for improving our pasture lands should be implemented and grazing in forest areas should be minimized because cattle damage young seedlings and saplings which may be useful for regeneration in future, and their hooves increase soil compactness, thereby increasing soil erosion and runoff.

- Forest floor litter should not be removed or burned because it helps in the formation of a heavy humus layer, which act as a reservoir of nutrients, helps retain water and protects the soil against erosive forces.
- Reclamation of acidic, saline and sodic soils should get priority in the areas that are affected by these problems in different states. The ameliorative materials should be made available according to the severity of the problem in the districts/states.
- Where complex problems of degradation like water erosion, acidity and water erosion, salinity and sodicity co-exist, the research agenda needs to be reoriented to bring out a list of "good practices" for amelioration of soil health of such degraded lands.
- Cultivation of bio-fuel producing plants and fuel trees/crops in degraded lands and wastelands should be encouraged. This is an essential step for environmental protection. The datasets and maps of this study can help district authorities to plan activities accordingly.
- Minerals and mining explorations should be carried out in degraded areas so that fertile lands can be protected from deterioration. Lands that have turned to wastelands due to mining should be reclaimed with suitable technologies, and appropriate land use plans may be drawn up for better utilization of such landscapes.

Land degradation aggravates the processes that ultimately lead to related complications in the Himalayan region. Addressing the issue may not solve the problem entirely, but can definitely ease the situation provided appropriate measures are taken. Tewari and Kapoor (2013) suggest that such an initiative needs to:

- identify and tag site specific issues to adequately address the different facets of the problem;
- adopt a multi-disciplinary approach combining theoretical and applied knowledge in all the relevant domains as the key strategy for understanding the complex human environment systems;
- should be institutionalized, financially coherent and socially acceptable;
- be meaningful, consistent and coherent across all the sectors and related actors.

Hence it is desirable to think, plan and work for the long-term sustainability of this unique ecosystem in order to conserve resources on one hand and secure the future of humanity on the other.

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Estimation of soil erosion dynamics in the Koshi Basin using GIS and remote sensing

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Abstract

High levels of water-induced erosion in the transboundary Himalayan river basins are contributing to substantial changes in basin hydrology and inundation. Basin-wide information on erosion dynamics is needed for conservation planning, but field-based studies are limited. This study used remote sensing (RS) and a geographic information system (GIS) to estimate the spatial distribution of soil erosion across the entire Koshi basin, to identify changes from 1990 to 2010, and to develop a conservation priority map. The revised universal soil loss equation (RUSLE) was used in an ArcGIS environment with rainfall erosivity, soil erodibility, slope length and steepness, crop management, and support practice factors used as primary parameters. Estimated annual erosion increased from 376,951 t/ha/yr in 1990 to 435,996 t/ha/yr in 2010. The results were within the range of reported levels derived from isolated plot measurements and model estimates. Erosion risk was divided into eight classes from very low to extremely high and mapped to show the spatial pattern of soil erosion risk in the basin in 1990 and 2010. The erosion risk class remained unchanged between 1990 and 2010 in 87% of the study area, but increased over 9.0% of the area and decreased over 3.8%, indicating an overall worsening of the situation. Areas with a high and increasing risk of erosion were identified as priority areas for conservation. The study provides the first assessment of erosion dynamics at the basin level and provides a basis for identifying conservation priorities across the Koshi basin. The model has a good potential for application in similar river basins in the Himalayan region.

Introduction

Land degradation, sedimentation, and ecological degradation tend to increase as a result of inappropriate land use and management practices (Zhao et al., 2005; Quan et al., 2011). Information on the spatial distribution patterns and dynamic changes in erosion is useful for developing plans and determining priorities for controlling soil erosion at the river basin level. Soil erosion is contributing to substantial changes in basin hydrology and inundation (Nibanupudiand and Rawat, 2012) in the transboundary Himalayan river basins, and the problems are compounded by social, economic, and political changes (Pimentel et al., 2000). Water-induced erosion in the mountain and hill areas of these basins is very high (Montgomery, 2007; Gardner and Gerrard, 2003; Eswaran, Lal and Reich, 2001) as a result of the steep slopes (Lves and Messerli, 1989) as well as terrace agricultural practices with poor management. The rivers in the region transport heavy loads of sediment (Jain, Kumar and Varghese, 2001; Narayana and Babu, 1983; Sen, Rao and Saxena, 1997; Carson, 1985; Jasrotia and Singh, 2006; Dabral, Baithuri and Pandey, 2008) which are deposited downstream, leading, for example, to the formation of islands in the Ganges and Brahmaputra delta (Lves and Messerli, 1989; Shrestha et al., 2004b). Soil erosion has been reported to affect crop production, and also leads to sedimentation in dams (Gregg and Izaurralde, 2010; Bakker et al., 2008; Lal, 2003; Lal, 2008).

The Koshi basin extends from the Tibetan Plateau in China, through Nepal, to the Gangetic plains in India. It has a diverse topography, geology, and geomorphology and a wide range of land use practices, and is also strongly affected by soil erosion, sediment transport, and land degradation (Jain and Sinha, 2004; Sinha, 1996; Sinha, 2009; Nayak, 1996). The land and water resources of the basin are at risk as a result of rapid population growth, deforestation, soil erosion, sediment deposition, and flooding (Ries, 1995; Sinha, 2009; Uddin and Shrestha, 2011) and are not used as effectively as they could be to improve the livelihoods and socioeconomic conditions of the local people (Gibling et al., 2005). Studies based on small-scale erosion assessments using field or model-based methods have reported high erosion rates in the middle mountains of Nepal, which includes the most susceptible part of the Koshi basin (Ramsay, 1987; Jha and Paudel, 2010). The distinct topography and land cover scenario of the basin means that there are three different erosion regimes: 1) the high mountains with steep to moderate slopes and predominant land cover of grass, snow, and glaciers; 2) the middle mountains with steep to moderate slopes and predominant land cover of forest and agriculture; and 3) the low hills and plains with predominant land cover of agriculture.

Information on erosion patterns across the basin is needed in order to identify conservation priority areas. However, few field measurements have been carried out using standardised protocols, and none over the whole basin, and there have been very few studies of any sort assessing erosion at the basin level, or analysing the spatial trends in erosion and the relationship to land use practices and rainfall regimes. Most studies on erosion in the Koshi basin have focused on the middle mountains of the Nepal Himalayas because of the topography, land use dynamics, and high spatial and temporal variability in rainfall (Jain et al., 2001; Gardner and Gerrard, 2003; Franklin, 2001). Although a number of researchers have attempted to fill the gap in erosion data at various scales (Gardner and Gerrard, 2003; Shrestha, Zinck and Van Ranst, 2004a; Higaki, Karki and Gautam, 2005; Dabral et al., 2008), none have presented information on erosion patterns and dynamics for the entire basin.

Spatial information on erosion dynamics and quantitative information on soil erosion at the river basin scale is potentially very useful for planning soil conservation, erosion control, and management of the basin environment. But soil erosion management strategies in the Koshi basin are constrained by the scarcity and fragmented nature of the available data. It is important to identify the most sensitive areas in the Koshi basin for soil erosion so that effective conservation measures can be taken to address the problem but this is methodologically challenging. Soil erosion can be estimated using empirical or physically-based models. Empirical soil erosion models include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), Agricultural Nonpoint Source model (AGNPS) (Young et al., 1989), Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991), and Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). In theory, physically-based models have an advantage over empirical models because they can be combined with physically-based hydrological models. Fully distributed physical models such as Water Erosion Prediction Project (WEPP) and Agricultural Non-Point Source Model (AGNPS) perform better than equation models, but the cost of computation is high and they require a large amount of input at high spatial resolution (Rabia and Harb, 2012; Jha and Paudel, 2010). Complete listings and descriptions of different soil erosion models can be found in Roo, Utrecht and Wetenschappen (1993). The empirical RUSLE model remains the most popular tool for assessing water erosion hazards due to its modest data demands and easily comprehensible model structure, especially in developing countries where the possibilities for applying more complex models are often limited by a lack of adequate input data. In recent decades, RUSLE and its adapted versions (Renard et al., 1991; De Vente and Poesen, 2005) have been applied worldwide in different regions and at various spatial scales. The RUSLE–GIS interface has several advantages in terms of easy updating, integration of spatially referenced data, and the facility to present the mapping results in different forms. A number of studies have shown good results using RUSLE together with GIS and RS to model soil erosion (e.g., Adediji, Tukur and Adepoju, 2010; Perovic et al., 2013; Khosrowpanah et al., 2007; Pandey, Chowdary and Mal, 2007; Setegn et al., 2009).

There have been a number of studies of soil erosion in parts of the Koshi basin within the Nepal Himalayas. RUSLE has been used successfully to assess soil erosion in the Trijuga (Sah 1996) and Kulekhani (Singh et al., 2004) watersheds. Satisfactory results have also been obtained using the Revised Morgan, Morgan and Finney (RMMF) model in the Pakhribas (Sherchan and Chand, 1991) and Hamsingha Khola (Dhungana, 2002) watersheds and the Likkhu Khola valley (Shrestha, 1997), and RUSLE in the Bagmati basin (Jha and Paudel, 2010). Quincey and others (Quincey et al., 2007) used the Limburg Soil Erosion Model (Jetten and de Roo, 2001) to estimate soil erosion in the Pokhare Khola watershed at mid elevations, and high and medium spatial resolution optical images were used to assess erosion-prone areas in the Mustang watershed (Uddin, Dhakal and Joshi, 2014). RUSLE and RMMF were also applied to the Kalchi Khola watershed to predict soil loss rates and the spatial erosion pattern (Jha and Paudel, 2010). All of these studies attempted to estimate erosion at the level of a small watershed. In the present study, we used the RUSLE model together with remote sensing (RS) and GIS to make a basin-wide assessment of erosion dynamics in the Koshi river basin to determine priority areas for soil conservation and erosion prevention.

Materials and methods

Study area

The Koshi river basin lies between 85.02° and 88.95° E longitude and 25.33° and 29.14° N latitude, with a total area of 88,518 km^2 (Figure 1). It extends from the Tibet Autonomous Region in China, through Nepal, to Bihar State in India, and has seven major sub-basins: the Tama Koshi, Arun, Dudh Koshi, Likhu, Tama, Sun Koshi, and Indrawati. The basin contains rich biodiversity and is a source of valuable ecosystem services that sustain the lives and livelihoods of millions of people in China, India, and Nepal (Wahid, Nepal and Mishra, 2013). The basin has five distinct landscapes: the Tibetan plateau, high mountains, middle mountains, low mountains and hills, and plains or Terai. The digital elevation model (DEM) from the shuttle radar topographic mission (SRTM) shows an elevation range of 21 to 8,848 m, and slopes ranging from 0 to 88.76 degrees. About 15% of the basin area has a slope of more than 30 degrees. The climate in the northern and southern parts is different. Most of the basin is characterized by heavy precipitation during the monsoon season (June to September) when more than 80% of annual precipitation (Yamamoto et al., 2013) occurs, but the extreme north lies in the rain shadow plains and arid hill areas of Tibet. The maximum and minimum annual average precipitation in the basin is 3078 mm and 207 mm respectively. The average outflow of the Koshi river is estimated to be 47.2 km^3/year (Deka, 2007).

Data processes

Combining the Universal Soil Loss Equation and GIS

USLE and RUSLE are widely used to estimate rill erosion on overland flow areas (Foster, Toy and Renard, 2003; Rapp et al., 2001; Bagarello et al., 2011; Wischmeier and Smith, 1978) and RUSLE was used to assess the spatial patterns of erosion risk in the study area. Recent advances in GIS and remote sensing technology have enabled a more accurate estimation of the factors used in the calculation (Desmet and G, 1996; Nearing, 1997). Each of the factors was derived separately in raster data format and the erosion calculated using the map algebra functions. Figure 2 shows the framework for the RUSLE model calculation.

RUSLE is expressed as given in (Wischmeier and Smith 1978):

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where, **A** is estimated average soil loss in t $ha^{-1}yr^{-1}$., **R** is the rainfall-erosivity factor, **K** is the soil erodibility index, **L** is a slope length factor (dimensionless), **S** is a slope steepness factor (dimensionless), **C** is a land cover management factor (dimensionless), and **P** is a supporting practices factor (dimensionless).

The RUSLE parameters were calculated using separate equations with input generated from satellite images and a DEM. The input data, their sources, and the equations used, are listed in Table 1. The equations available in the literature for calculating the factors were tested iteratively and the optimal equations chosen based on their suitability for use with the data available and ability to produce estimates comparable to published field-based erosion measurements. The calculation of the individual factors is described in more detail in the next sections.

Table 1: **Input data, sources, and equations used to calculate the RUSLE factors**

Factor	Input data	Data source	Equation used
Rainfall erosivity factor (**R**)	Precipitation (ESRI grids, 10 arc-minutes)	World climate precipitation data (Reed, Johnson-Barnard and Baker 2010)	R = 0.0483*P1.610 where P= annual precipitation (mm)
Soil erodibility factor (**K**)	Soil maps from Nepal, India, and FAO		Literature review
Slope length factor (**L**)	SRTM 90 m digital elevation data	(SRTM 2008)	$L = (\lambda/22.13)^m$ where λ is the field slope length (m), and m assumes a value from 0.2 to 0.5 (Sing et al., 1981)
Slope steepness factor (**S**)	SRTM 90m digital elevation data	(SRTM 2008)	S = (0.43 + 0.30 s + 0.043 s2)/6.613 (Wischmeier and Smith, 1978)
Land cover management factor (**C**)	NDVI from Landsat TM and ETM+	(GLOVIS 2008)	C = 0.431– 0.805*NDVI (Renand et all 1997b)
Support practice factor (**P**)	Land cover map	ICIMOD (Uddin et al., 2015)	Literature review

Rainfall erosivity factor (R)

The rainfall erosivity factor (R) describes the erosivity of rainfall at a particular location based on the rainfall amount and intensity. This is an important parameter for soil erosion risk assessment under future land use and climate change (Meusburger et al., 2012). The average annual rainfall was calculated by summing the monthly rainfall data obtained from WorldClim; the R-factor was derived using equation (2) (McGarigal, 2002).

$$R = 0.0483 \times P1.610 \qquad (2)$$

where **P** = annual precipitation (mm).

Figure 3a shows the rainfall erosivity factor map derived for the study area.

Soil erodibility factor (K)

The soil erodibility factor (K) is a quantitative description of the inherent erodibility of a particular soil type; it is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff (Lane et al., 1992). The main soil properties influencing the K factor are soil texture, organic matter, soil structure, and permeability of the soil profile. For a particular soil, the soil erodibility factor is the rate of erosion per unit erosion index from a standard plot. In this study, K values at soil order level were computed from the published literature on mountain areas (Franklin, 2001; Gardner and Gerrard, 2003; Khosrowpanah et al., 2007; Jain et al., 2001; Mandal and Sharda, 2011). The erodibility of various soil types in the Koshi basin is given in Table 2. Figure 3b shows the spatial distribution of the soil erodibility factor in the study area.

Table 2: **Erodibility factors for different soil classes in the Koshi basin**

Soil type	Erodibility factor (K-factor)
Udalfs (alfisols) Orthents (entisols)	0.1
Orthents(E) Aquepts (incepti)	0.2
Aquepts(i) Ochrepts (inceptisols)	0.1
Orthents (entisols) Ochrepts (inceptisols)	0.15
Orthents (e) Aquepts(i) Ochrepts (i)	0.1
Orthents (e) Fluvents(0.17)/entisols	0.2
Psamments (0.2)/entisols	0.15
Aquepts (i) Fluvents (e)	0.2
Aquepts (i) Ochrepts (i)	0.1
Orthent s(e) Aquepts (i) Ochrepts (i)	0.1
Aquepts (i) Ustalfs (a)	0.1
Ustalfs (a) Ochrepts (i)	0.15
Aquepts (i) Ochrepts(i) Orthents (e)	0.15
Udalfs (a)	0.15
Aquepts (i) Ustalfs (a) Udalfs (a)	0.1
Orthents (e) Aquepts (i) Ustalfs (a)	0.15
Orthents (e)Tropepts	0.1
Ochrepts (i) Orthents(e) Udalfs (a)	0.15
Aqualfs (a) Fluvents (e) Aquepts (i)	0.2

Slope-length factor (L)

The SRTM DEM for the study area was used to calculate the slope length and slope steepness factors. The slope-length factor (L) represents the effect of slope length on erosion. The study area has an elevation range from 21 to 8,848m (SRTM 2008). L is the ratio of field soil loss to the corresponding soil loss from a 22.13 m length on the same soil type and gradient and is estimated using equation (3).

$$L = {}^{\lambda}/_{22.13})^{m} \quad (3)$$

Where, λ is the field slope length, and **m** has a value between 0.2 and 0.5.

Wischmeier and Smith (Wischmeier and Smith, 1978) have described various ways of determining m for different slopes and these have been applied in the Indian subcontinent (Singh, Chandra and Babu, 1981; Jain et al., 2001). In the present study, the value taken for m was based on the slope gradient and determined using the slope map as input.

Slope gradient	Value of m
1%	0.2
1–3%	0.3
3–4.5%	0.4
4.5% or more	0.5

The field slope length λ was taken as the SRTM grid size (90 m); thus the slope length was calculated using equation (4).

$$L = (90/22.13)^m \quad (4)$$

Figure 3c shows the spatial distribution of the slope length factor in the study area.

Slope-steepness factor (S)

The slope-steepness factor (S) represents the effect of slope steepness on erosion. Soil loss increases more rapidly with slope steepness than it does with slope length. S is the ratio of soil loss from the field gradient to that from a 9% slope under otherwise identical conditions. The relationship of soil loss to gradient is influenced by the density of vegetative cover and soil particle size. The S factor is calculated using the equation (5) as described in (Wischmeier and Smith, 1978) :

$$S = (0.43 + .30s + 0.043s^2)/6.616 \quad (5)$$

where **s** is the slope in percent.

Figure 3d shows the spatial distribution of the slope steepness factor in the study area.

Cover management factor (C)

The cover-management factor C is used to reflect the effect of cropping and management practices on erosion rates. Vegetation cover is the second most important factor next to topography controlling soil erosion risk (Van der Knijff, Jones and Montanarella, 1999). The land cover intercepts rainfall, increases infiltration and reduces rainfall energy. The C factor is normally assigned based on the type and density of vegetation cover. This approach transforms land cover into discrete weighted data. We used the method proposed by De Jong (1994) to generate the cover management factor (C) using the Normalized Difference Vegetation Index (NDVI) calculated from Landsat TM and ETM+ images from 1990 and 2010:

$$C = 0.431 - 0.805 * NDVI \quad (6)$$

Where NDVI = near infrared (NIR) – red (R)/ near infrared (NIR) + red (R).

Figures 4a and 4b show the spatial distribution of the cover-management factor in the study area in 1990 and 2010.

Support practice factor (P)

The support practice factor P reflects the impact of support practices, i.e. soil conservation operations or other measures to control erosion, on the erosion rate. It is measured as the ratio of soil loss with a specific support practice to the corresponding loss with straight row ploughing up and down slope (Renard et al., 1997b;

Prasannakumar et al., 2012). The P factor map was prepared using land cover maps for 1990 and 2010 prepared from Landsat TM and ETM+ images using object based image analysis (Uddin et al., 2015b; Bajracharya et al., 2010; Uddin et al., 2015a) (Figures 5a, b). The support practice factors were then assigned using the land cover maps together with published data (Jain et al., 2001; Franklin, 2001; Renard et al., 1997a; McGarigal, 2002; Sonneveld and Nearing, 2003; Renard et al., 1991; Wang et al., 2000; Dissmeyer and Foster, 1981; Brown and Foster, 1987).

Variation of support practice factor for 1990 and 2010 is given in Figures 5c and 5d respectively.

Figures 5c and 5d show the spatial distribution of the support practice factor in the study area for 1990 and 2010.

Results

Soil erosion risk maps were developed for the entire Koshi basin using RUSLE in conjunction with GIS and RS. The results are shown in Figures 6a (1990) and 6b (2010). The study area was divided into eight erosion risk classes, from very low to extremely high, based on the estimated erosion rates. The total soil loss for the entire Koshi basin area was estimated to be 376,951 t in 1990 and 435,996 t in 2010. The southern area of the basin was less erodible, and the central area highly erodible. The differences in erosion levels between the northern, central, and southern parts of the study area are mainly due to topography. The areas in the very low erosion class were mainly located at the lower elevations where the terrain is relatively flat. The maximum per hectare average soil loss occurs at elevations between 1,000 and 2,000 m and the minimum at elevations between 70 and 100 m. Table 3 shows the estimated soil loss from different land cover classes in 1990 and 2010. The maximum soil loss rate is from barren land, around 22 t/ha/yr. The total soil loss from barren land was estimated to be 155,147 t in 1990 and 179,333 t in 2010. The total soil loss from agricultural land was estimated to be 105,572 t in 1990 and 127,047 t in 2010.

Table 3: **Land cover and estimated erosion rates in the Koshi Basin in 1990 and 2010**

Land cover	Land cover (km^2)		Mean erosion rate (t/ha/yr)		Annual soil loss (t/ha/yr)	
Year	1990	2010	1990	2010	1990	2010
Forest	19,827	20,032	0.3	0.5	6,145	9,215
Shrubland	670	679	3.4	3.9	2,285	2,648
Grassland	23,486	23,463	4.6	5.0	107,329	117,548
Agricultural land (kharif)	15,691	17,927	2.5	3.4	38,915	61,133
Agricultural land (rabi)	14,715	11,708	4.5	5.6	66,658	65,914
Barren land	7,081	8,245	21.9	21.8	155,147	179,334
Built-up area	268	99	0.05	0.08	13	8
Water bodies	572	793	0.71	0.19	406	151
Snow/glacier	5,235	4,595	0.01	0.01	52	46
Total	**87,542**	**87,542**			**376,951**	**435,997**

Table 4 shows the transformation of area between erosion risk classes between 1990 and 2010 in the form of a change matrix. The area that remained constant in the different erosion classes is shown in the shaded diagonal cells. Close to 87% of the study area remained in the same erosion risk class. The proportion of the area at very low risk of erosion went down from 62.4% in 1990 to 60.5% in 2010, while the area at extremely high risk of erosion increased from 1.8% to 1.9%. The erosion risk increased over 9.0% of the area, and decreased over 3.8%, indicating that overall the situation is worsening.

Table 4: **Change matrix for erosion risk classes from 1990 to 2010 (%)**

Soil erosion risk rank (ton/ha/yr)	Very low (<0.5)	Low (0.5–1)	Low medium (1–2)	Medium (2–5)	High medium (5–10)	High (10–20)	Very high (20–50)	Extremely high (>50)	Total 2010
Very low (<0.5)	58.61	0.76	0.22	0.19	0.10	0.13	0.24	0.30	60.55
Low (0.5–1)	1.97	4.33	0.31	0.03	0.00	0.00	0.00	0.00	6.64
Low medium (1–2)	0.33	0.48	4.59	0.34	0.00	0.00	0.00	0.00	5.74
Medium (2–5)	0.30	0.12	0.49	6.67	0.32	0.01	0.00	0.00	7.90
High medium (5–10)	0.30	0.05	0.11	0.76	4.54	0.34	0.01	0.00	6.10
High (10–20)	0.38	0.02	0.07	0.26	1.03	3.70	0.34	0.00	5.80
Very high (20–50)	0.40	0.01	0.02	0.12	0.22	0.97	3.43	0.17	5.33
Extremely high (>50)	0.19	0.03	0.01	0.01	0.03	0.04	0.32	1.30	1.94
Total 1990	**62.47**	**5.80**	**5.82**	**8.38**	**6.23**	**5.20**	**4.33**	**1.77**	**100**

It is important to determine priority areas for conservation as a basis for decision making for soil and water conservation over the entire basin. The need for conservation is based on both the risk and changes in erosion patterns. In this study, we combined current erosion risk, changes in erosion risk, and actual estimated erosion to determine priority areas for conservation. A higher priority was assigned to areas where erosion risk is increasing and vice versa. The multicriteria decision rules for identifying conservation priorities were identified as described by others Wang et al. (2013).

Figure 7 shows the conservation priority map obtained using this approach. The areas in the two top priority levels for conservation cover 7,758 km^2 or close to 9% of the basin area. They are mostly found in the central part of the basin at mid elevations. This area has the greatest intensity of agriculture and has seen a marked increase in erosion risk. Areas in the top two priority levels need to be managed in future projects as erosion control regions using appropriate conservation strategies. The third and fourth levels include areas with high but close to constant levels of erosion and cover 11% of the study area. These regions only need a minor allocation of funds for controlling soil erosion in future projects. The lowest two priority levels cover 66% of the basin area (57,397 km^2) and represent areas with a low risk and level of erosion. These areas will only require erosion control if the risk level increases, for example, as a result of changes in land use.

Discussion

The only field data available for assessing erosion in the Koshi basin come from catchment level studies carried out at single points in time. There are no basin wide data available, and most studies have focused on areas in the middle mountains of Nepal where topography is irregular and there is a high degree of spatial variability of rainfall (Jain et al., 2001; Gardner and Gerrard, 2003; Franklin, 2001; Ghimire, Higaki and Bhattarai, 2013). There have been no basin-wide studies of erosion or erosion dynamics that can be used to determine priority areas for conservation activities. The present study shows that the RUSLE based assessment method, using remotely sensed data and automated analysis of land cover and slope gradient, can be used as the best alternative to field-based measurement to estimate erosion risk across an entire river basin, and that the results can be used to help identify priority areas for controlling soil erosion. Although many factors influence water erosion, the vegetation cover, slope gradient, and land use play the most important role in erosion resistance or risk (Wang et al., 2013; De Vente and Poesen, 2005). The model can be applied to similar river basins in the Himalayan region following appropriate calibration and validation.

It was not possible validate the estimates and analyse error and bias by comparing model estimates with field-based measurements over a set of sites because there have been very few field-based studies in the basin. Spatial estimates would be useful to assess the spatial variability of erosion and prioritize the areas of conservation. The results were compared with the estimated erosion levels of different land cover classes derived from published field data on plot level erosion measurements (Gardner and Gerrard, 2003; Ghimire et al., 2013; Anup et al., 2013) and model based results (Shrestha, 1997; Kunwar, Bergsma and Shrestha, 2002; Acharya and Kafle, 2009), mostly pertaining to mid and high hill areas in Nepal with similar characteristics to the Koshi basin. Table S1 shows that the RUSLE derived estimates were within the range given in the published studies. However, the mid hills of Nepal are extremely heterogeneous in terms of rainfall distribution, topography, soil, and cultural practices, and this leads to a high variation in erosion levels. Thus one-to-one comparison of the estimates over a set of sites is essential for proper validation.

In future, the model could be further refined by addressing some of the limitations in the estimation of the various factors, especially rainfall, slope length and steepness (L,S), and soil erodibility factors, which are the major drivers of erosion in RUSLE.

The rainfall erosion potential is basically controlled through the product of total storm energy and maximum 30-min storm intensity. In the absence of detailed rainfall data at sub hourly interval, as well as the absence of specific equations for the Koshi basin for the rainfall erosion factor, we used annual rainfall-based equations suitable for hilly areas.

There are several equations available to estimate slope length factor from a digital elevation model. Most of these were found to overestimate erosion. We chose the equation that gives the best estimate compared to the published literature. However the LS factor is one of the most important variables for erosion estimation and should be calibrated over the study area to increase the reliability of the quantitative estimates.

The soil erodibility factor K was weighted at soil order level using published results (Panagos et al., 2012; Khosrowpanah et al., 2007; Mandal and Sharda, 2011; Ghimire et al., 2013). Better estimates can be made of K if information is available on soil texture and organic carbon. The cover-management and support practice factors (C, P) are more site-specific and broadly match the generic properties of a site.

In addition, the RUSLE method is reported to overestimate erosion in high terrain. The RMF and MF models have been reported to yield better estimates over hilly terrain but require extensive ground data and calibration. A holistic discussion is needed on the accuracy required in erosion estimates in order to plan appropriate model and ground measurements.

Conclusion

The results show that the RUSLE based assessment method can be used as the best alternative for erosion assessment when there are no suitable field-based measurement data. A conservation priority map was prepared based on the estimated erosion and erosion dynamics from 1990 and 2010, which can be used to support the planning of conservation interventions and sustainable management practices. The model can be applied to similar river basins in the Himalayan region following appropriate calibration and validation.

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Author contributions

All authors listed contributed sufficiently to the project to be included as authors, and all those qualified to be authors are listed as such.

Conflicts of interest

To the best of our knowledge, no conflict of interest, financial or otherwise, exists. The findings are the results of a scientific study and observations by the authors and do not necessarily reflect the views of the International Centre for Integrated Mountain Development.

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Table 1: Input data, sources, and equations used to calculate the RUSLE factors

Mountain soil degradation in Myanmar

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Abstract

A large part of Myanmar falls within the HKH region, which is characterized by steep mountain slopes, upland plateaus, undulating areas, valleys and lowland deltaic area. Deforestation, mineral extraction and shifting cultivation are the major drivers of soil degradation in Myanmar. Land degradation in upland areas is caused by soil erosion, water erosion and soil fertility depletion. The Myanmar government is trying to address land degradation through different policies such as community forestry and Reducing Emission from Deforestation and Degradation (REDD+); establishment of forest plantations and the Myanmar Reforestation and Rehabilitation Program (MRRP); and also through promoting sustainable forest management (SFM), forest conservation and afforestation and reforestation, including watershed management programs, establishment of permanent forest estate, Myanmar Timber Legality System and Forest Law Enforcement Governance Trade (FLEGT) and land use planning and land policy formulation. Watershed management contributes to natural forest conservation and soil and water conservation activities over the watershed area of 53 dams/reservoirs throughout the country. The National Land Use Policy will address current land use management and land tenure issues for a five-year period and will be updated at least every five years to reflect changing circumstances.

Status of land degradation

A large part of Myanmar falls within the Hindu Kush Himalayan Region, which is characterized by steep mountain slopes, upland plateaus, undulating areas, valleys and lowland deltaic area. Most of the ranges stretch from North to South and the country's drainage system comprises four major rivers – the Ayeyawady, Chindwin, Sittaung and Thanlwin – which also flow from North to South in association with the complex terrain. The Ayeyawady River and its major tributary, the Chindwin River, constitute the greatest river system in Myanmar. In general the country has abundant water resources, and watershed management is given high priority.

The total land area of Myanmar is 67.66 million hectares, and 70% of the country's total population is engaged in the agriculture sector, according to 2014 Myanmar Population and Housing Census (DOP, 2015). Although Myanmar has abundant arable land with good soil for agriculture and horticulture, there are increasing problems related to soil fertility and land degradation in mountainous areas.

Land degradation in upland areas is caused by soil erosion, water erosion and soil fertility depletion. The mountain environment is under threat from both human activities and climate change. Land degradation lowers land productivity and the land ultimately becomes unproductive. In an agrarian country like Myanmar, decrease in the productivity of agricultural land is a serious issue and immediate action is required to conserve and restore land (Mg Mg Than, 2015). Technical and institutional issues related to land management should be addressed in order to fulfill sustainable development goals related to soil issues in the Hindu Kush Himalayan region.

Deforestation

At present the mountain area remains covered with natural forests. However, there has been a steady decline in forest cover. Underlying drivers include poverty, economic growth and increasing consumption, capacity constraints, lack of environmental safeguards, unclear land tenure and weak enforcement of land laws, undervaluation of biodiversity, and lack of grassroots participation in conservation-related decision-making processes.

Mineral extraction

Mining is the most significant economic activity in some mountain areas with important mineral resources and it also produces high-quality gems and precious stones. Exploitable reserves of industrial minerals are also available. Industrial-scale commercial land use and small-scale gold mining are expanding. While new mines today are generally subject to strict environmental controls, older mines and areas abandoned after earlier mining continue to cause environmental problems. There is limited monitoring of the impact of landslide and soil and water pollution.

Shifting cultivation

Growth in the upland human population is a key pressure, being closely correlated with land degradation and land productivity changes. From 1980 to 2008, upland population increased by 7 million, reaching 17.5 million people, or accounting for about 30% of the national population.

Ethnic minority communities have been practicing shifting cultivation from time immemorial and it is closely related with theirs socio-cultural identity. However, in the past, they practiced shifting cultivation in the same area with a fallow period of 15–20 years, which ensured the long-term sustainability of soil fertility, and ensured forest regret. With the rapid growth in population, the fallow period has been dramatically reduced to 3–4 years, allowing very little time for soil or vegetative regeneration.

Soil erosion under abandon shifting cultivation areas (taung - ya, phone zoe and fallow) in east and west Bago Yoma watershed areas found low soil fertility levels in soil and high soil loss rate according to the ratings of soil loss values. Fallow area does not have significant effect on the soil's inherent susceptibility to eroding forces. This may be related to the regeneration of the secondary growth that protects the soil from raindrops and facilitates accumulation of soil organic matter. (FRI, 2015)

In the case study of Kalawchaung watershed region in south Shan state, soil loss rates increased with the cultivation time, at the rate of 26 t/ha/yr. Soil erosion reached 120 t/ha/yr after 40 years of conversion – from forest land to cropland. The results show significant soil losses on the upper slopes and soil accumulation in the lower areas closer to the lake (IAEA and Forest Department Cooperation Project, 2016 (MYA 2015)). There is little information available on soil degradation in Southern Chin State due to the effect of shifting cultivation, which has destroyed most of the forests below 2,000 m above sea level and is threatening Natmataung National Park.

Climate change

Myanmar's vulnerability to climate change is now widely recognized with a clear trend of rising temperatures, shortening of monsoon duration, and increased frequency of intense rainfall and severe cyclones along Myanmar's coastline. The most productive upland areas in Myanmar are prone to damage by cyclones and landslides, which threatens crop production. The effects of climate change on some mountain areas have caused extreme events including landslides, cutting of roads and burying of farmland in Chin State. Efforts must be made to rehabilitate agricultural land in these areas given the fragile environment.

Policy measures

The Government of Myanmar is implementing a range of policies and measures to address deforestation and forest degradation – namely, community forestry, Reducing Emission from Deforestation and Degradation (REDD+); establishment of forest plantations, and Myanmar Reforestation and Rehabilitation Program (MRRP). In addition, the government is promoting sustainable forest management (SFM), forest conservation and afforestation and reforestation, watershed management programs, establishment of permanent forest estate, Myanmar Timber Legality System and Forest Law Enforcement Governance Trade (FLEGT) and land use planning and land policy formulation. (Mg Mg Than, 2015)

Watershed management is very important in mountain areas. The forest department has endeavored to conserve and rehabilitate forested areas in watersheds to ensure sustainability of watersheds and prevent sedimentation in dams and reservoirs. This involves formulation and implementation of Action Plans for Establishing Watershed Plantation in Watershed Area of Major Dams, Reservoirs and Water Sources every five years. The Action Plan not only seeks to establish watershed plantation, but also to conduct natural forest conservation and soil and water conservation activities over the watershed area of 53 dams/reservoirs throughout the country.

For the land use sector of Myanmar, the government has set up the National Land Use Policy, which applies to all land resources, improvements, uses and tenures in the country, in both rural and urban areas. The National

Land Use Policy guides the development of new land legislation, including the National Land Law, as well as harmonization and implementation of all existing land use and land tenure laws. It also guides and integrates all branches of government and ministries involved in land use and land tenure decision making matters, including regional, state and local and government. The policy will address current land use management and land tenure issues for a five-year period and will be updated at least every five years to reflect changing circumstances.

Challenges to soil conservation

There should be monitoring and evaluation of the sources and impact of land degradation so that governmental agencies and local communities can work further on the issue. Although local NGOs and INGOs have conducted soil conservation activities through integrated farming practices and agro forestry techniques in hotspot areas, they do not cover remote areas. Capacity building and awareness raising programs are needed to ensure active participation of upland farmers. Technical guidelines for soil conservation models should be established at the regional and national level for a sustainable agriculture system in the hilly region. Forest soil mapping is very important for soil conservation but Myanmar only has an agriculture soil map. Resource persons and advanced technology are needed for forest soil mapping. Financial resources to reduce risk and mitigate the effects of climate change are also necessary.

Way forward

A long-term capacity building program and action plan for soil conservation activities will be developed for the whole region. Research on the diversity and strengths of Myanmar's shifting cultivation system will be encouraged, and collaborative research on sustainable land use practices will be conducted with international governmental agencies. Soil conservation guidelines will be introduced in different farming systems. An REDD+ activities network involving community people will be established for sustainable forest management.

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Changes in physical properties of soil on forest floors as a result of landslides caused by the Wenchuan earthquake

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Abstract

A strong earthquake seriously disturbs local soil-forest ecosystems. However, there is limited information on this, especially on changes in soil physical properties of forest floors in earthquake-induced landslide areas. It is useful for us to know how difficult ecological restoration is in disaster areas. Therefore, an experiment was conducted in the northern section of the fault belt formed by the Wenchuan Earthquake of China. Fifteen plots 20 m × 20 m in size were set up in *Cupressus funebris* and *Cryptomeria fortunei* plantations located in landslide and non-moved areas near the fault belt. The landslide and non-moved plots were fairly close to each other. Within each plot, five points were determined at the centre and near the four corners for soil sampling. Each soil sample was collected from 0-10 cm, >10-20 cm and >20-40 cm depths at each of the points in all the plots. The samples were taken in June and October 2009. Soil bulk density, total porosity, capillary porosity, non-capillary porosity, and water content, saturated water content, capillary moisture capacity and field water capacity were measured in the lab. The study revealed that bulk density increased and total porosity, capillary porosity, water content, saturated water content, capillary moisture capacity and field water capacity decreased in the landslide soils compared to the non-moved soils. *Cupressus funebris* soil had higher bulk density but the other properties were lower compared to those of *Cryptomeria fortunei* soil. None of the properties underwent seasonal change in 2009. These results indicate that soil structure was more seriously damaged in the landslide areas and the soils became tight and dry, but the changes varied across forests. *Cupressus funebris* soil had weaker capacity for water retention and the soil-forest ecosystems of the species would be more variable in the future.

Introduction

A great earthquake (>7.0 Ms) not only causes human and economic losses but also seriously impacts local ecosystems, including soil-forest ecosystems. However, there has been relatively little information on the effects of earthquakes, especially on earthquake-induced landslide areas where a large number of trees are disturbed but not completely destroyed and some of them will either gradually die or regenerate over time.

Soil physical property is easily damaged by an earthquake. For example, after the occurrence of the Wenchuan Earthquake (8.0 Ms) in China on 12 May 2008, soils became loose and fell away due to huge mass movements. Meanwhile, soil aggregate stability decreases in disaster areas.

Soil physical property is one of the important factors that influence plant growth and survival. For example, plant growth is critically restricted by soil drought. On the other hand, tree root systems play positive roles in soil formation, structure and stability. The effects vary across tree species due to the differences in their root architectures. Generally, large and dense root systems have greater ability to maintain soil structure and resist a natural disturbance than relatively superficial root systems. How a great earthquake impacts soil physical properties of various forest floors and whether seasons, such as the rainy season, impact the disturbed soils after a great earthquake are poorly understood, but such information is important for us to know how the disturbed soil-forest ecosystems will change in the future.

To that end, an experiment was conducted with *Cupressus funebris* and *Cryptomeria fortunei* forests located in landslide and non-moved soils in the northern section of a roughly 300 km long fault belt caused by the Wenchuan Earthquake. Both species were among the dominant tree species in the area. Soil physical properties were examined in July and October of 2009 to evaluate changes in soil structure in different disturbed soils, in both forests and in the summer and fall season.

Materials and methods

Site description

The study area was located in the northern section (Fig. 1). It extended between E104°16′5.95″ -104°28′27.95″ and 31°38′51.55″-N31°49′47.95″ and elevated between 759 m and 1397 m. The mean annual precipitation ranged from 1261 mm to 1399 mm, and the mean annual temperature was from 15.6°C to 16.3°C.[1]

A total of 15 plots were established at three sites (I, II and III) near the fault belt (Fig. 1). Each plot was 20 m × 20 m in size. At site I, two of the plots were located in *Cupressus funebris* and *Cryptomeria fortunei* plantations, respectively, in non-moved soil. At site II, three plots were set up in *Cupressus funebris* plantation in landslide and non-moved soils, respectively. At site III, two plots were established in *Cryptomeria fortunei* plantation located in landslide soil, and three for the forest in non-moved soil. The plots in the landslide and non-moved soils were fairly close to each other at sites II and III. The landslides were moved 20 m to 60 m down from the upper elevations. All the plantations had approximately 0.5 m × 0.5 m density and were 23-27 years old.

Figure 1: Study area with research sites (dots) in the northern section of fault belt of the Wenchuan Earthquake, China

Soil sample collection

Within each plot, five points were determined at the centre and near the four corners inside the plot for soil collection, except for some points with rock and stone substrates. At each point, three intact soil cores with a 100 cm^3 volume (5 cm in diameter, and 5 cm in height) were taken from the surface layer (0-10 cm, >10-20 cm) and the subsurface layer (>20-40 cm in depth), respectively, to investigate soil physical properties. Meanwhile, a 20 g soil sample was taken for water content measurement using an aluminum box at each point in each layer. The soil samples were collected in June and October 2009.

Measurements of soil physical properties

In this study, the following properties were investigated: soil bulk density, total porosity, capillary porosity, non-capillary porosity, water content, saturated water content, capillary moisture capacity and field water capacity.

Water content was determined by soil samples in the aluminum boxes. The fresh and dry soil weights of the boxes were measured using a digital balance before and after drying in an oven at 105-110°C for 72 h.

For the measurements of saturated water content, capillary moisture capacity and field water capacity, each of the soil cores was covered with a filter paper at the bottom and was placed on a tray with water to be absorbed. Until all the non-capillary and capillary were full of water (about 12 h), m_1 was obtained by weighing the core immediately. Sequentially, the core with the paper was placed on a dry tray for 2 h to remove non-capillary water from the soil; m_2 was obtained by weighing the core at that time. Thirdly, the core was placed on a dry tray again for another 24 h to continuously take soil water out, and was weighed to obtain m_3. Fourthly, the core was dried in an oven at 105-110°C for 72 h to gain m_4 by weighing. Finally, net weight of the soil samples was measured and defined as m. The parameters of m, m_1, m_2, m_3 and m_4 were used to calculate soil saturated water content by Eq. (1), soil capillary moisture capacity by Eq. (2), field moisture capacity by Eq. (3) and soil bulk density by Eq. (4), respectively.

Total porosity, capillary porosity and non-capillary porosity of soil were calculated by Eqs. (5, 6 and 7). The equations were as follows:

$$S_W = \frac{m_1 - m_4}{m_4 - m} \times 100\% \quad (1)$$

$$C_W = \frac{m_2 - m_4}{m_4 - m} \times 100\% \quad (2)$$

$$F_W = \frac{m_3 - m_4}{m_4 - m} \times 100\% \quad (3)$$

$$D = \frac{m_4 - m}{V} \quad (4)$$

$$P_t = \left(1 - \frac{D}{D_s}\right) \times 100 \quad (5)$$

$$P_c = C_W \times \frac{D}{V} \times 100 \quad (6)$$

$$P_n = P_t - P_c \quad (7)$$

Where S_W, C_W and F_W are for soil saturated water content (%), capillary moisture capacity (%), and field water capacity (%), respectively. P_t, P_c and P_n are for total porosity (%), capillary porosity (%) and non-capillary porosity (%). V is the volume of soil core (100 cm^3); D is for soil bulk density (g/cm^3); D_s is for soil particle density of 2.65 g/cm^3 [2].

Results

Soil bulk density and porosity

Soil status and forests statistically influenced the soil bulk density and total porosity (Table 1). Soil bulk density was significantly lower in the non-moved soils (1.17 g/cm^3) than in the landslide soils (1.26g/cm^3). The density was slightly different between *Cupressus funebris* and *Cryptomeria fortunei* soils, and was lower in *Cryptomeria fortunei* soils (1.02 g/cm^3) than in *Cupressus funebris* soils (1.41 g/cm^3). *Cryptomeria fortunei* soils had significantly higher total porosity, capillary porosity and non-capillary porosity (60.97%, 46.11% and 14.06%) than *Cupressus funebris* soils (47.08%, 37.07% and 8.49%) (Table 2). Total porosity and capillary porosity were higher (55.32%, and 44.19%) in the non-moved soils than in the landslide soils (51.89% and 38.99%) (Table 2). Interactions of soil statues × forests showed that in *Cupressus funebris*, non-capillary porosity was higher in the landslide soils compared to the non-moved soils (Fig. 2).

Table 1. Analysis of covariance for effects of seasons (June and October), soil status (non-moved and landslide soils), soil depth (0-10 cm, >10-20 cm, and >20-40 cm), forests (*Cupressus funebris* and *Cryptomeria fortunei*) and their interactions on soil physical properties in the section in 2009. Altitude (759-1,397 m) is the covariate for removing the effects of the elevational climatic difference in the data. Bolded number indicates a significant difference ($P<0.05$).

Source	Soil density (g/cm^3)	Total porosity (%)	Capillary porosity (%)	Non-capillary porosity (%)
Altitude	**0.000**	**0.000**	0.510	**0.000**
Seasons (T)	0.477	0.381	0.759	0.363
Soils (S)	**0.001**	**0.001**	**0.000**	0.439
Forests (F)	**0.000**	**0.000**	**0.000**	**0.000**
Depth (D)	0.060	0.062	0.919	0.545
T×S	0.643	0.543	0.583	0.917
T×F	0.827	0.743	0.387	0.373
S×F	0.880	0.887	0.106	**0.041**
T×S×F	0.284	0.233	0.715	0.768
T×D	0.728	0.667	0.932	0.961
S×D	0.757	0.695	0.649	0.442
T×S×D	0.951	0.897	0.830	0.925
F×D	0.793	0.810	0.887	0.844
T×F×D	0.533	0.500	0.597	0.690
S×F×D	0.839	0.796	0.740	0.709
T×S×F×D	0.430	0.380	0.735	0.598

Figure 2: The interactive effect of soil status × forests on non-capillary porosity

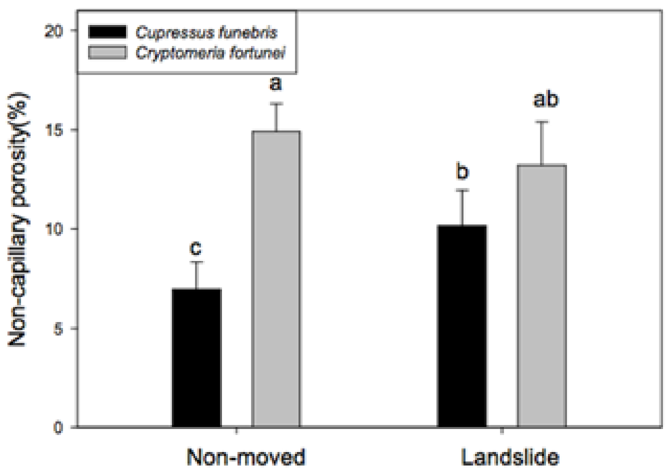

Table 2. The main effect of seasons, soil status and forests on physical properties. The mean values and their standard errors (± S.E.) are shown. Bolded number indicates a significant difference (P<0.05). Means with the same letter have no differences between them.

Source		Soil density (g/cm³)	Total porosity (%)	Capillary porosity (%)	Non-capillary porosity (%)
Seasons	June	1.22[a] ±0.02	53.22[a] ±1.01	41.78[a] ±0.87	10.55[a] ±0.02
	October	1.21[a] ±0.02	53.94[a] ±1.01	41.40[a] ±0.87	11.66[a] ±0.02
Soils	Non-moved	1.17[b] ±0.02	55.32[a] ±0.87	44.19[a] ±0.69	10.57[a] ±0.01
	Landslide	1.26[a] ±0.03	51.89[b] ±1.25	38.99[b] ±0.99	11.64[a] ±0.03
Forests	*Cupressus funebris*	1.41[a] ±0.03	47.08[b] ±0.99	37.07[b] ±0.79	8.49[b] ±1.13
	Cryptomeria fortunei	1.02[b] ±0.03	60.97[a] ±1.14	46.11[a] ±0.91	14.06[a] ±1.29

Soil water properties

Soil status and forests statistically influenced soil water porosity (Table 3). Soil water content was significantly different between the two seasons and lower in June (25.03%) than in October (33.22%) due to the rainy season (Table 4). The water content, saturated water content, capillary moisture capacity and field water capacity were higher (31.06%, 42.27%, 38.59% and 37.37%) in the non-moved soils than in the landslide soils (26.98%, 35.96%, 31.00% and 31.61%). *Cryptomeria fortunei* soils had a higher water content, saturated water content, capillary moisture capacity and field water capacity (37.86%, 51.76%, 46.40% and 44.77%) than *Cupressus funebris* soils (21.29%, 29.38%, 25.78% and 24.22%) (Table 4).

Table 3. Analysis of covariance for effects of seasons (June and October), soil status (non-moved and landslide soils), soil depth (0-10 cm, >10-20 cm, and >20-40 cm), forests (*Cupressus funebris*, *Cryptomeria fortunei*) and their interactions on soil water properties in the section in 2009. Altitude (759-1397 m) is the covariate for removing effects of the elevational climatic difference in the data. Bolded number indicates a significant difference (*P*<0.05).

Source	Water content (%)	Saturated water content (%)	Capillary moisture Capacity (%)	Field water Capacity (%)
Altitude	0.006	0.000	0.000	0.000
Seasons (T)	0.000	0.768	0.954	0.319
Soils (S)	0.019	0.001	0.000	0.004
Forests (F)	0.000	0.000	0.000	0.000
Depth (D)	0.884	0.335	0.411	0.388
T×S	0.916	0.345	0.557	0.479
T×F	0.861	0.937	0.572	0.466
S×F	0.209	0.338	0.181	0.150
T×S×F	0.016	0.770	0.550	0.958
T×D	0.610	0.575	0.751	0.872
S×D	0.711	0.818	0.910	0.941
T×S×D	0.952	0.997	0.978	0.823
F×D	0.530	0.754	0.915	0.684
T×F×D	0.998	0.480	0.586	0.712
S×F×D	0.805	0.777	0.875	0.855
T×S×F×D	0.929	0.653	0.711	0.664

Table 4. The main effect of seasons, soil status and forests on soil water properties. The mean values and their standard errors (±S.E.) are shown. Bolded number indicates a significant difference (P<0.05). Means with the same letters have no significant difference between each other.

Source		Water content (%)	Saturated water content (%)	Capillary moisture capacity (%)	Field water capacity (%)
Seasons	June	25.03[b] ±1.06	39.22[a] ±1.03	34.54[a] ±1.03	35.33[a] ±1.19
	October	33.22[a] ±1.06	38.77[a] ±1.03	34.64[a] ±1.03	33.65[a] ±1.19
Soils	Non-moved	31.06[a] ±0.86	42.27[a] ±1.41	38.59[a] ±1.21	37.37[a] ±1.13
	Landslide	26.98[b] ±1.24	35.96[b] ±2.03	31.00[b] ±1.74	31.61[b] ±1.63
Forests	*Cupressus funebris*	21.29[b] ±0.99	29.38[b] ±1.62	25.78[b] ±1.39	24.22[b] ±1.30
	Cryptomeria fortunei	37.86[a] ±1.13	51.76[a] ±1.86	46.40[a] ±1.56	44.77[a] ±1.49

Soil physical properties with depth

Soil depth did not influence the soil bulk density (Table 1) and soil water porosities (Table 4) in any of the plots.

Discussion and conclusion

Effects of landslides on soil bulk density and porosities

The study reveals that the soil structure obviously changed in the landslide areas. Soil bulk density was significantly higher in the landslide soils. Thus the soils became tight. The change was attributed to gravitation that generated high pressure on the soils when the lands suddenly moved down. Another possible reason is that bedrocks might move up to the ground by shakes resulted from the hundreds of aftershocks, since many small rocks and stones were found in the surface and subsurface layers during soil collection. This result is opposite in other earthquake-disturbed soils, which become loose (such as areas of debris flow) and collapse. It suggests that soil physical properties changed differently in different hazarded areas of the Wenchuan Earthquake.

In the landslide soils, total porosity and capillary porosity decreased, implying that the capacity for soil water retention decreased. Low capillary porosity weakens the transportation of capillary water from the lower to upper soil layer, and importantly inhibits available water uptake by tree roots.

Our result supports previous studies that found that vegetation significantly affects soil physical properties.[3] *Cryptomeria fortunei* soils had higher total porosity, capillary porosity, non-capillary porosity, and lower soil bulk density than *Cupressus funebris* soils. Therefore, *Cryptomeria fortunei* soils have a higher capacity for water retention and the species would better acclimate to earthquake-induced landslides and can regrow faster than *Cupressus funebris*.

Effect of landslides on soil water properties

All the examined water properties were lower in the landslide soils than in the non-moved soils (Table 3). This is due to the fact that rainfall runoff increased and water infiltration reduced in the surface layer of the landslide soils with high bulk density.[4] Additionally, water transportation from the lower to upper soil declined. As a result, the landslide soils became dry, and drought may be more serious in the upcoming years.

The water properties were lower in *Cupressus funebris* soils than in *Cryptomeria fortunei* soils. The landslide soil of *Cupressus funebris* was drier than that of *Cryptomeria fortunei*. *Cupressus funebris* would suffer from a decrease in soil water supply. Since July 2009, some of *Cupressus funebris* forests have gradually died in the landslide areas, which may be related to soil drying.

Effects of soil depth on physical properties

Generally, soil bulk density increases and soil porosities decrease with increasing soil depth.[5] Table 2 shows that no differences in density and porosities occurred among the three soil layers in the landslide and non-moved soils. That may be due to the effects of gravitation as discussed above. For the non-moved soils, the lack of differences may be due to the fact that the earthquake and aftershocks homogeneously impacted the soils in these layers.

Effects of seasons on physical properties

Soil bulk density and porosities did not change between June and October, and nor did soil water properties; only soil water content increased during the rainy season. The results suggest that the soil physical properties were not further degraded until the fall of 2009. But it is difficult to conclude that degradation of soil-forest ecosystems stopped. Future studies would be required to determine this.

Potential impacts of landslide soils on ecosystems

Soil tightening not only inhibits tree root extension for soil resource availability,[6] but also reduces soil aeration,[7] which inhibits the growth and activities of aerobic microorganisms, and alters nutrient cycling in the soils. For example, nitrifying bacteria as aerobic bacteria grow difficultly, and denitrifying bacteria as anaerobic bacteria grow rapidly in the compacted soils.[8] This situation may accelerate N loss and reduce plant growth rapidly in the landslide soils.

Conclusion

Earthquake-induced landslide soils become tight and dry a year later. After the earthquake, soil physical properties of forest floors undergo different changes, which may result in the different restoration processes of both forest ecosystems. Soil chemical properties may also change after the earthquake. How the complex changes in the soil environment impacts forest ecosystems remains unknown and needs further research, as it is associated with the quality of the environment and consequently the lives of local people.

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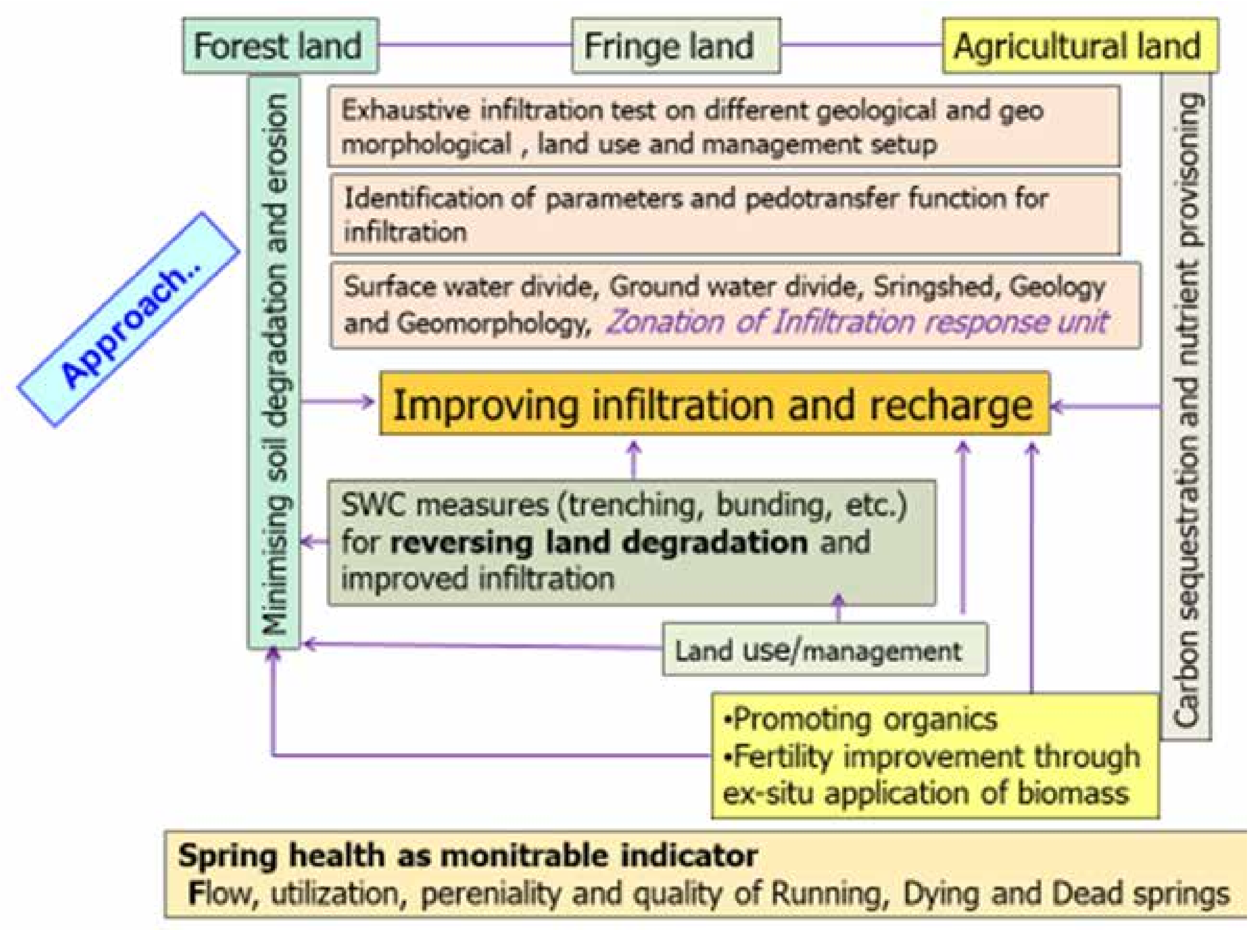
Theme: Watershed management

Stepping Towards Effective Watershed Management: Integrated Approach

- Integrated watershed management can contribute in reducing land degradation and improving the quality of life and livelihood opportunities not only for upland mountain people but also in downstream areas.
- The governments of countries in the HKH region along with regional and international organizations are intensifying their approach for conservation of water in upland areas whose economies depend predominantly on agriculture.



Principle and practices of watershed management in Nepal: Efforts to reverse mountain soil degradation

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Abstract

Watershed resources are the foundation of the livelihood and prosperity of mountain people. Watershed components are linked with various hydrological, geological and landscape characteristics along with socioeconomic components, therefore, comprehensive planning at the broader river basin level should be done to address multiple watershed issues. Various community-based conservation efforts as well as national and international efforts have been made in the past. Being a mountainous country, Nepal has also made various efforts of watershed management for a long time. WSM policies and practices in Nepal have been developed through various stages, from scattered activity based WSM, to integrated river basin management (IRBM), to integrated watershed management (IWM), and carried out through participatory approaches. Current WSM has been broadened to climate change adaptation, water-induced disaster mitigation, nature-based solutions to environmental problems, ecosystem-based adaptation, incentivizing environmental services, and wise use of water resources. Thus, these environmental problems must be studied scientifically. Designing an IRBM framework at the central level, strategic planning at the provincial level, and micro-watershed level intervention at the local level should be ensured with collaboration and coordination among stakeholders and effective public partnership. Finally, providing education and raising the awareness of local people to involve them in watershed planning and mobilization of local resources is crucial for sustainable river basin management.

Introduction

Land, water and vegetation are major watershed resources. Management of watershed resources needs an integrated approach to land management, soil productivity enhancement, erosion control, water conservation, vegetation manipulation as well as consideration of various socio-economic factors (Campbell, 2016). Sustainable watershed management is crucial for maintaining a balance between human needs and nature conservation (Said et al., 2006).

Land degradation and soil fertility losses are prominent problems associated with food security and the well-being of mountain people. More than 2 billion hectares of land is estimated to be degraded worldwide, affecting the livelihood of more than a billion people (Reddy et al., 2017). Similarly, more than 3 million hectares of Nepal's land area is undergoing degradation (Acharya and Kafle, 2009). Land degradation, diminished land productivity, and water related issues pose a significant threat to achieving global goals of sustainable development (Kust et al., 2017; Zambon et al., 2017).

More than half of the rural population in Asia, especially poor people, lives in mountains (Thapa, 2001). The problem of soil erosion and land degradation is persistent in mountainous countries, including Nepal. Land degradation is not only caused by biophysical and climatic factors but also triggered by socioeconomic factors and land use practices. Watersheds are the most suitable planning as well as management units to address soil and water related issues, especially in the mountain region (Thapa, 2001; Pirani and Mausavi, 2016). In this scenario, watershed management (WSM) aims to solve watershed problems, such as soil degradation, erosion and sedimentation, water scarcity, water induced disasters, and other bio-physical and hydrological problems on a sustainable basis (Said et al., 2006; Pandit et al., 2007).

Soil degradation in Nepalese mountains

The nature of soil erosion varies across regions because of the tectonic activities in the Himalayas (Andermann et al., 2012). Likewise, peak rainfall rate also prompts geomorphic processes such as landslide and mass wasting (Olen et al., 2015). Only a few studies have been done to measure site-specific erosion rates from the mountains of Nepal. For instance, annual soil erosion in the Koshi Basin is reported to be 42 million tonnes as of 2010 (Uddin et al., 2016). Sediment yield from the Karnali River is estimated to be 4,362 tonnes/sq.km/year (Sangroula, 2009). Erosion fluxes in Nepal are estimated to range from 260±26 to 4,706±1274 tonnes/sq.km/year (West et al., 2015). A study by Gardner and Gerrard (2003) estimated that annual soil loss ranges from 2.7 ton/ha to 12.9 tonnes/ha from rain-fed agricultural terraces of the middle hills of Nepal. Similarly, another estimate mentioned that surface erosion from agricultural land varies significantly, ranging from 2 to 105 tonnes/ha/year from the hilly region of Nepal (Acharya et al., 2007). Soil loss rate for specific sites in Nepal is presented in Table 1.

Table 4: **Soil loss rate by location and land condition (NFA, 2016)**

SN	Description of location and site, land condition	tonnes/ha/year
1	Siwaliks, east Nepal, south aspect sandstone foothills	7.8-39.8
2	Siwaliks, mid-western Nepal, south aspect sandstone foothills	
	degraded forest	20
	degraded forest, gully land	40
	severely degraded heavily grazed forest, gully land	200
3	Mahabharat Lekh, central Nepal, very steep slopes on metamorphic and sedimentary rocks	
	degraded forest	31.5-140
	gully lands	63-420
4	Middle mountains, Kathmandu valley, northern foothills of granites and migmatite with weak consolidation	
	degraded forest and scrubland	27-45
	dominantly overgrazed scrubland	43
	severely gullied land	12.5-57
5	Middle mountains, western region of Nepal, south aspect moderately steep slopes on parallel dipping phyllitic schist	
	protected pasture	9.2
	overgrazed grassland	22-34.7
	gully and overgrazed grassland	29

Land use change, deforestation and intensification of agricultural activities are closely linked with soil erosion in mountains (West et al., 2015). More than half of the agricultural land in Nepal lies in the hilly region (Acharya et al., 2007). Agriculture in the hilly region, which occupies 12.1 percent of the total area of the country (LRMP, 1986), is important in determining soil loss from mountains. For instance, soil erosion from well-managed terraces ranges from 5-10 tonnes/ha/year whereas erosion from poorly managed terraces ranges from 20-100 tonnes/ha/year (Leban, 1978). A study by the DSCWM recommended that 19 percent of currently cultivated land should not be cultivated, 61 percent of agricultural land needs proper drainage, and 23 percent of agricultural land needs proper terracing (Sthapit, 1994).

Much of soil loss and sedimentation in Nepal is triggered by landslide, flooding, and mass wasting. Landslide covers an estimated area of 55 sq. km in the hills and mountains, which greatly contributes to the large amounts of sediment in the lowlands (Sthapit, 1994). Similarly, river bank cutting is estimated to affect an area of 16,398 sq.km, and slumping and gulling are estimated to affect an area of 4,244 sq.km. Additionally, wind erosion is expected to affect an area of 4,249 sq.km of land in Nepal (Sthapit, 1994). Those various forms of geo-morphological and hydrological processes have created several problems of soil loss in the upstream and sedimentation in the downstream.

Development of WSM in Nepal

Historically, traditional farming practices have ensured the conservation of soil and water resources in Nepal. However, soil and water conservation has gained national importance since 1974, with the establishment of the Department of Soil Conservation and Water Management (DSCWM) by the government. Since then, WSM has been included in many development plans, conservation strategies, policies and legislations (Pandit et al., 2007).

Accordingly, the government of Nepal has established and restructured various organizations over time in order to plan and manage watershed resources and ensure wise use of such resources.

WSM policies and practices in Nepal have been developed through various stages, from scattered activity based WSM, to integrated river basin management (IRBM), to integrated watershed management (IWM). WSM practices in Nepal can be visualized through the following phases.

Before 1970: Activity-based WSM (traditional agricultural practices)

As Nepal has historically been an agrarian country, most people's means of livelihood and major economic activities were based on agricultural practices. WSM is considered to be as old as agricultural practices (Reddy et al., 2017). However, major activities were limited to terrace farming, agroforestry, and other traditional practices for land productivity enhancement. Traditional agronomic practices such as farmyard manuring, multiple cropping, bunding, plantation of fodder tree species, and pond construction were major interventions before WSM was planned. A few projects on hydropower dams and construction of large-scale irrigation schemes triggered the concept of WSM planning in Asia (Reddy et al., 2017). Accordingly, conservationists in Nepal also started to focus on the problems of soil erosion and sedimentation to some extent. A few activities on soil and water conservation were carried out but they lacked holistic planning and sufficient efforts to address the country's need for comprehensive watershed management and development.

1970-1990: Project-based WSM (greenery promotion and livelihood)

The decade of the 1970s was regarded as the time of accelerating green revolution and food security (Reddy et al., 2017). Realizing the problem of mountain degradation and the need for land restoration, the Third Five-Year Plan (FYP) of Nepal (1965-1970) mentioned the importance of WSM and the need to plan soil conservation activities, especially in the uplands of Nepal (Pandit et al., 2007). Accordingly, various project-based conservation activities were implemented, focusing on greening the degraded watershed and providing livelihood support. Backed by the objectives of the periodic plan of Nepal and lessons from the projects, the government established the DSCWM as a responsible leading institution for soil and water conservation and watershed management in Nepal. Later in 1993-1997, the DSCWM was reorganized for widening the scope of WSM. Though it seemed like a symbolic approach, the Shivapuri watershed was given priority for conservation by forming the Watershed Development Board in 1976 (Pandit et al., 2007). Likewise, participatory conservation was promoted in nationally important watersheds such as Kulekhani and Phewa watersheds. WSM was also included in various integrated rural development projects (IRDP), such as *Mahakali* IRDP, *Sagarmatha* IRDP and *Rapti* IRDP. Soil conservation and watershed management gained much attention in various national policies. Accordingly, Soil Conservation Act 1982 and Regulation, 1985 were promulgated. Although the legislative measures became inactive and WSM couldn't be applied throughout the country, this phase was important in drawing the attention of political actors to WSM and defining a participatory approach for conservation.

1990 to 2010: Programme-based WSM (upstream-downstream linkages and IWM)

This period is important for institutionalizing soil and water conservation activities through a programme approach. This phase has been a cornerstone in articulating environment policies, watershed prioritization and planning, and community soil conservation programmes. Geo-morphological features of the country was recognized and addressed in national planning. For instance, the Chure[1] region received political attention for conservation and development. Likewise, realizing the need of upstream-downstream linkages, the WSM approach was extended from uplands to lowlands as well. IWM has been taken as the principle approach to consider bio-physical and socio-cultural aspects of the watersheds collectively. Various low-cost soil conservation and bio-engineering techniques were developed to mobilize local resources and local people for WSM.

Various conservation policies were formulated and implemented in the early 1990s. National Conservation Strategy 1987, Master Plan for Forestry Sector 1988, National Environment Policy and Action Plan 1995, and Forestry Sector Policy 2000 focused more specifically on soil conservation and watershed management. Environmental assessment of development and economic activities has been ensured by national laws during that period. The eighth FYP

[1] Chure is the youngest hills formed by the deposition of river products from around four crore years ago. It occupies about 12.78% of the total land of Nepal.

(1992-1997) focused on a participatory approach to conservation through formation of community groups, and conservation education and extension activities were intensively conducted in that period. District Soil Conservation Offices were established in various districts to provide soil conservation and watershed management services. Moreover, the involvement of non-governmental sector was also encouraged in that period. Yet the success of WSM is yet to be evaluated. Environmental sensitivity and watershed issues were incorporated in various national policies, plans and programs.

2010 to present: climate resilience and IRBM

Impacts of climate change and water stress have been major concerns in many countries including Nepal. Current WSM has been broadened to climate change adaptation, water-induced disaster mitigation, nature-based solutions to environmental problems, ecosystem-based adaptation, incentivizing environmental services, and wise use of water resources. In order to address those multiple aspects, a broader river basin approach has been the current conservation discourse in Nepal. Currently, policy makers and conservation partners are discussing broad IRBM based on the principles of integrated water resource management and IWM.

Actors and institutions for WSM

The DSCWM is the leading governmental organization mandated for sustainable watershed management through maintaining ecological balance and land productivity. However, other governmental organizations also work for multiple water use, irrigation management, and water induced disaster management. The DSCWM is equipped with multidisciplinary personnel from various academic and professional backgrounds, foresters, civil engineers, agriculturists, geologists, chemists, and administrative field. It has been conducting soil conservation and WSM activities nationwide through District Soil Conservation Offices (DSCOs) in 61 districts. Most of the WSM activities are carried out through a participatory approach, through the formation of community groups. Those community groups contribute at least labour support while implementing conservation activities conducted by the DSCOs.

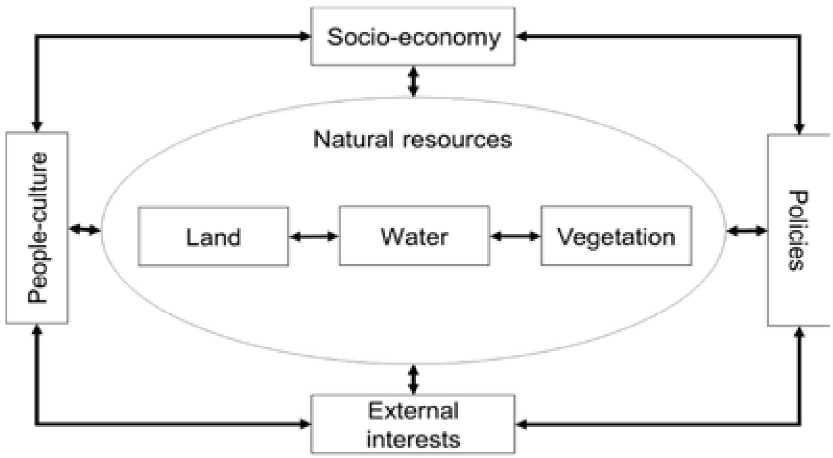
Besides, the Water and Energy Commission Secretariat, Department of Water Induced Disaster Prevention, and Department of Hydrology and Meteorology are also involved in research and development for WSM programs. Moreover, various conservation partners have been involved in WSM activities in Nepal. The United Nations Development Program and the Food and Agricultural Organization were involved in the planning and extension of IWM. The Finnish Development Agency, Danish International Development Agency as well as Japan International Cooperation Agency were involved in participatory planning and implementation of IWM policy. Swiss Development Cooperation and German Development Assistance supported in community level planning and mobilization of poor and socially excluded people. Likewise, the International Centre for Integrated Mountain Development, IUCN-Nepal, CARE-Nepal, and WWF Nepal have been involved in developing appropriate soil conservation techniques and management measures; research activities and supporting government organizations to implement IWM programs.

WSM programmes and activities

WSM has broader scope, and accordingly, IWM is considered to be a promising approach for achieving the resource management objectives of the watershed, considering natural resources (forest, land, agriculture, water), human resources as well as other social, economic and institutional aspects of the watersheds (Figure 1). IWM is also considered to be an advanced approach for land rehabilitation and for maximizing resource objectives (Haregeweyn et al., 2012). Accordingly, participatory IWM has been a core approach for managing watershed resources in Nepal.

WSM is broad in terms of defining the programmes and activities within watersheds. It depends on typical hydrological aspects and geological and morphological characteristics of a region. Reddy et al. (2017) mentioned that technically WSM can be divided into three major categories: soil conservation, in-situ moisture conservation, and water harvesting structures. In Nepal, major WSM program activities include conservation farming, farm-forestry, bio-engineering and community mobilization (Wagley and Bogati, 2000). Likewise, the DSCWM's working guideline divided WSM activities into five broader categories, namely, land use planning, land productivity enhancement, development infrastructure protection, prevention of natural hazards and participatory soil conservation (Pandit et al., 2007). Major program activities of the DSCWM and its district offices are shown in Table

Figure 1: Components of IWM



2.

Table 5: **WSM programme activities**

SN	WSM programmes	Activities
1	Watershed management planning	Reconnaissance, semi-detailed and detailed level planning; Participatory and log-frame based planning
2	Land use development plans	Strategic, watershed, sub-watershed, micro-watershed and community level
3	Disaster Risk Reduction and Natural Hazards Management	Landslide Inventory and Documentation; Hazard Mappings, Vulnerability Assessment and Risk Mapping; Landslide Treatment; Gully Treatment; Torrent Control; River/ Stream Bank Protection
4	Sustainable Land Management	Degraded Land Rehabilitation; Diversion Channel Construction; On-farm Conservation; Fruit Tree Plantation; Fodder/grass Plantation; Nursery/Seedling Production; SALT Plot Establishment and Management; Sustainable Soil Management; Conservation Plantation; Silvi-Pasture Improvement
5	Water and Sediment Management	Siltation Management; Ground Water Recharges Structure Construction
6	Development Infrastructure Protection	Irrigation Channel Protection; Trail Improvement; Road Slope Stabilization; Shelterbelt Development; Buffer Strip Development
7	Climate Change Adaptation / Resilience Development	Water Source Protection and Development; Catchment Restoration; Conservation Pond; River bed Farming; Wetland Conservation; Rain-fed Farming; Run-off Harvesting Dam Construction
8	Community Mobilization, Capacity development and Livelihood Improvement	Conservation Income Generation Program; Community Mobilization/Empowerment; Conservation Farmers Network Establishment; Agro-forestry Development; Partnership Soil Conservation; Small Enterprise Development; Study Tour and Trainings; Conservation Education Campaign; Training/ Workshop/ Exposure Visit; Conservation Women Training/ Workshop/ Exposure Visit
9	Research, Technology Development and Extension	Natural System Monitoring; Action Research on Conservation; Bio-engineering Plot Establishment and Management; Conservation Demonstration; Conservation Farming; Conservation Exhibition/Extension; Conservation Day Celebration; Conservation Extension Material Production
10	Monitoring and Evaluation	Monitoring of Soil Conservation and Watershed Management Program; Coordination Workshop and Meeting; Joint Monitoring and Learning; Case Study Documentation and Sharing; Public Auditing and Self Evaluation; Revision of the Document

Source: DSCWM, 2015

Achievements of WSM activities

Soil and water conservation programme is considered to be a satisfactory achievement based on the review of the master plan for the forestry sector of Nepal (MFSC, 2014). Enhanced public awareness and people's participation is one of the major achievements of the DSCWM. Growing concern at the policy level and institutionalization of WSM activities from the national to local level is also an important achievement of the DSCWM. Various conservation and development activities targeting poor and marginalized people have remarkably contributed to the livelihood of the people. Similarly, institutional strengthening, systematic development of conservation technologies, livelihood and capacity building of community people, soil erosion control, natural hazards management and land productivity enhancement are other considerable achievements of WSM activities. Some of the major quantitative achievements of the DSCWM since its establishment in 1974 are in Table 3.

Table 6: **Some of the major outputs of DSCWM**

SN	Description/activities	Units	Quantity
1	Watershed management plans	plans	520
2	Gully/landslide treatment	places	6667
3	River bank control	km	4660
4	Run off harvesting dam	places	72
5	Water source protection	sources	4268
6	Conservation pond/ wetland protection	places	2357
7	On-farm conservation	ha	5222
8	Degraded land rehabilitation	ha	16050
9	River bank land conservation	ha	2347
10	Road slope stabilisation (Bio-engineering techniques)	km	576
11	Irrigation canal protection and improvement	km	1937
12	Community soil conservation activities	places	3958
13	Sloping Agriculture Land Technology demonstration	ha	50
14	Conservation education programme	organizations	3555
15	Conservation training	persons	14660
Source: DSCWM, 2018			

Natural hazard prevention and conservation extension has been a major focus of WSM activities in Nepal. Likewise, WSM efforts are believed to have institutionalized various bio-engineering soil conservation techniques at the community level. However, due to scattered efforts of the DSCWM and lack of a clear mechanism for establishing input-output linkages for the WSM programme at the watershed level, it is still difficult to sum up the achievements of WSM programs in the language of public and policy makers.

Issues and challenges

Sustainable development can only be achieved through a clear match between conservation strategies and watershed reality (Budryte et al., 2018). Issues and challenges in WSM are deeply rooted in national policies as well as in the socio-economic condition of rural farmers (Thapa, 2001). Although the Soil Conservation Act and Regulation has been promulgated, it is considered to be a defunct policy and is not implemented properly, and there is a lack of specific policy guidance on WSM. Moreover, conservation scholars believe that the spirit of the Act is not reflected in the organizational development of the DSCWM. This is because while the Act has been envisioned for protected watersheds, the organizations have been extended based on administrative units, i.e. districts. In addition, WSM objectives could not be achieved due to lack of clarity in the regulatory mechanism (Pandit et al., 2007).

The success of WSM activities highly depends on inter-sectoral coordination at the field level (Msuya and Lalika, 2017). Streamlining of soil and water conservation activities at the local level is very important. However, lack of common understanding of the problems and weak coordination among stakeholders at the local level is considered to be major problems for IWM (MFSC, 2014). Weak capacity of local institutions and avoidance of indigenous knowledge are also considered to be primary causes of watershed degradation (Thapa, 2001). Some of the conservation efforts were supported by external agencies on a project basis, but past experience showed that the work could not achieve sustainability after the completion of the project (Paudel and Thapa, 2004; Thapa, 2001).

Adverse geological conditions and climatic characteristics lead to enormous soil loss and lowering of land productivity (Kayastha et al., 2013). Moreover, water scarcity has emerged as a serious problem in recent years (Thakur et al., 2017). Due to lack of a proper strategy, land use change and cultivation in marginal lands has exacerbated problems related to soil conservation and overall land productivity in watersheds (Paudel and Thapa, 2004). Rainfed terraces and degraded grazing lands in Nepal are posing a serious threat to soil conservation and overall land productivity (Thapa, 2001). Key problems of watershed development are related to water quantity and quality, ecological impacts, weak socio-economic conditions and lack of adequate public participation (Said et al., 2006).

Growing issues of climate change and disaster events are exacerbating the challenges for WSM in Nepal (Sharma and Shakya, 2006; Pumo et al., 2017). Nepal is very prone to landslide and floods, which are further accelerated by climate change impacts and human induced natural disasters. Due to the poor culture of integrating upstream-downstream linkages in watersheds, it is a big challenge to find comprehensive solutions to watershed problems (Pandit et al., 2007). Lack of adequate technical as well as financial investment in upstream areas, and an unclear financing mechanism pose constraints to sustainable WSM (Gautam et al., 2003; Esmail and Geneletti 2017).

A way forward

Nakicenovic et al. (2016) have noted that the environmental aspects of sustainable development goals (*life on land, life below water, climate action, and clean water and sanitation*), also called the Earth system, are non-negotiable goals as they are the pre-conditions for social and economic development. These environmental goals can be achieved through the successful implementation of WSM programmes (Msuya and Lalika, 2017). However, structural works as well as land-based technologies and forestry-based management systems remain inadequate. WSM should also address socio-cultural and economic aspects (Thapa, 2001).

In the first place, political will, strategic policy guidance and a clear regulatory mechanism are of utmost importance in defining and enhancing WSM programmes and activities. Chess and Gibson (2001) focused on attributes of scientific, social and motivational feasibility to guide an innovative approach to WSM. Strengthening of technical aspects for planning and designing WSM, considering hydrological and bio-physical components, must be a priority area of action (Reddy et al., 2017; Xie et al., 2017). A clear understanding of environmental problems and a scientific approach are necessary for solving the problems.

Watershed components are linked with various hydrological, geological and landscape characteristics along with socioeconomic components; therefore, there should be comprehensive planning at the broader river basin level to address multiple watershed issues. In the context of the changing government structure, designing an IRBM framework at the central level, strategic planning at the provincial level, and micro-watershed level intervention at the local level should be ensured. Accordingly, collective outcomes of watershed management can meet the objectives of IRBM. Coordination among stakeholders and effective public participation is the basic principle of IRBM. Constant dialogue between policy makers, practitioners and local people at the landscape level should be promoted for effective upstream-downstream linkages and watershed investment (Pandit et al., 2007; Ansink et al., 2017; Esmail and Geneletti, 2017). Public education and awareness raising so as to involve local people in watershed planning and mobilization of local resources is crucial for sustainable river basin management (Marshall and Duram, 2017; Euler and Heldt, 2018).

Conclusion

Mountain watersheds are undergoing degradation due to marginal land cultivation, land use change and other multiple climatic factors. Immediate actions of WSM are necessary to safeguard mountain degradation and enhance land productivity. IWM offers land-based solutions to many environmental problems at the watershed level. Nepal has been successful in implementing the principles of IWM and ensuring people's participation in WSM.

Strategic planning and clear regulatory mechanisms for managing watershed resources are essential for achieving the national goals of sustainable development. A broader integrated river basin approach and translation of IRBM principles into community-based practices are necessary for achieving sustainable socio-economic development. It is important to mainstream the principles of WSM into local farming practices in order to conserve soils and reverse mountain soil degradation. A common understanding of mountain problems and effective coordination among stakeholders, along with active community participation, can generate ample opportunities for reversing mountain soil degradation and ensuring the well-being of mountain people.

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Soil function: Infiltration and recharge

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Abstract

Water regulation and supply is one of the most important ecosystem services of the HKH region. Improving infiltration not only improves soil water storage, base flow, spring flow and ground recharge, it also reduces surface runoff, sealing, crusting, soil degradation, erosion, and floods. It is important to prevent splash erosion, surface crusting and sealing to maintain and improve soil structure and infiltration. Therefore, straw mulching, organic cultivation, ex-situ application of organic matter and conservation agriculture are options for cultivated land of the HKH region. Though high-density forest has been found to be associated with high quality water in streams, it is the moderate density forest that has the highest ground water recharge. Spring health in terms of rate of flow, perenniality, lean period flow and quality of water may be used as an indicator for water regulation function including infiltration and recharge. Higher infiltration and base flow under natural mixed vegetation in the hilly region as compared to introduced plantation suggests the need to identify forest type for improved infiltration and recharge. Reduced runoff and erosion, improved infiltration and lean period flow observed in mine-spoiled rehabilitation work carried out by ICAR-IISWC, Dehradun in the HKH region indicates high potential for up-scaling different technologies developed by research organizations working in the HKH region, including ICAR-IISWC, Dehradun, for sloping arable as well as non-arable land. Identification and mapping of infiltration and recharge favourable geological and geo-morphological conditions, identification of suitable forest type and vegetation, defining and mapping an infiltration response unit using a combination of land characteristics including land use, mapping spring sheds, evaluating the hydrologic footprint of different resource conservation technologies developed for arable and non-arable land and up-scaling suitable *in situ* soil and water conservation measures in watershed mode are the way forward for improving infiltration and recharge in the HKH region. The infiltration-recharge study in the context of land degradation and restoration in the HKH region fits well in the emerging conceptual framework of Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services (IPBES) for converting science to practice.

Introduction

The HKH region and the associated river basins provide water and other ecosystem services to almost one-fifth of the world's population. Soils, which are integral to many ecosystem services including water regulation, need to be maintained and managed in order to continue and improve their function. It is increasingly recognized that soil plays a fundamental role in the quality and distribution of our water supply. Soil, coupled with the landscape and its vegetation, is responsible for distributing all rainwater that falls on it. The nature of topsoil influences the runoff that fills lakes and rivers, and in extreme situations, leads to flash flood; it influences the entry of water, which either gets stored in soil for use by vegetation growing on it and by soil organisms, or percolates through soil to become part of ground water. The soil thus holds a key position with respect to our water supply cycle and is now seen as a key element of the ecosystem by hydrologists.

Figure 1: Soil functions

Most soil functions (Fig. 1) depend directly or indirectly on soil water retention and transmission, which explains their importance in many environmental processes within the Earth's critical zones. Soil hydraulic properties are essential in irrigation and drainage studies for closing water balance equation, for predicting leaching of nutrients, for water supply to plants, and for other agronomical and environmental applications. Soil hydraulic properties reflect the structure of the soil porous system comprising pores with different geometrical features and of various sizes. The geological characteristics of the Himalayas, with fractures and fissures in hard rock settings, play an important role in defining infiltration and recharge, culminating in spring discharge.

It is necessary to provide policy makers with evidences for converting science into practice for the protection of ecosystems in line with the newly emerging concept of the Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services (IPBES) (https://www.ipbes.net).

Importance of infiltration in soil quality

The ideal state of soil depends on the soil's ability to partition water and regulate infiltration, thus decreasing soil erodibility (Nearing et al., 1990). It has been suggested that the primary function of soil of high quality, relative to water erodibility, is to accommodate entry of water into the soil matrix through infiltration (Karlen and Stott, 1994). In assessing soil quality, infiltration is the most important indicator (Table 1).

Table 1: **Framework for assessment of soil functions (Mandal et al., 2010)**

Infiltration and redistribution of air and water	Preservation of soil moisture	Organic matter supply and nutrient cycling	Resistance to erosion	Habitat for flora and fauna
Infiltration or Redistribution (0.2)#	Soil Organic Carbon (0.3)	Soil Organic Carbon (0.2)	Veg. cover (0.2)	Soil Organic Carbon (0.2)
Bulk Density (0.2)	Veg. cover (0.3)	Veg. cover, (0.1)	Surface topography (%) (0.2)	Veg. cover (0.2)
Surface topography (0.1) Veg. cover (0.1)	Clay, % (0.3)	Macro fauna (0.2)	Infiltration or Redistribution (0.2)	Macro fauna (0.2)
Soil structure (0.1)	Surface stoniness (0.1)	Nitrogen, N (0.1)	Clay (0.2)	Soil structure (0.1)
Macro fauna (0.1)		Phosphorous, P (0.1)	Surface stoniness (0.1)	pH (0.1)
Clay (0.1)		Potassium, K (0.1)	Bulk Density (0.1)	Bulk Density (0.1)
Soil Organic Carbon (0.1)		pH (0.2)		Clay (0.1)

Figures in parentheses refer to weight assigned within the function

Soil quality in terms of entry of air and water and resistance to erosion has been found to be lowest in terraced agriculture of the mid-slope region in Himalayan watersheds (Mandal et al., 2010). Change of various soil functions with respect to undisturbed reference site was greater in the upper-slope region. It followed the order of habitat for flora and fauna (−35%) > preservation of soil moisture (−27.4%) > organic matter supply and nutrient cycling (−24.4%) > infiltration of air and water (−23.8%) > resistance to erosion (−9.0%). However, the trend of change in the mid-slope region was in the order of organic matter supply and nutrient cycling (−25.9%) > habitat for flora and fauna (−22.4%) > preservation of soil moisture (−16.3%), which indicates that ecologically relevant destruction took place in rain-fed old croplands in mid-slope and high slope positions.

If water is not infiltrated, it runs on the surface to cause erosion and degradation of soil structure, which increases soil erodibility, surface sealing, and crusting. Surface sealing and crusting reduces seedling emergence and infiltration. Reduced infiltration provides less opportunity for soil water storage. Therefore improved infiltration helps prevent a perpetual cycle of land degradation. Soil structure can determine both the effectiveness of farming practices and their impact on water infiltration and soil erodibility, which in turn depend on such soil physical properties as aggregation, bulk density, hydraulic conductivity, water-holding capacity, and porosity. All these properties depend on the amount and quality of organic matter in the soil. Water and solute movement is important to make the water available within the root zone and allow the movement of nutrients and beneficial soil organisms in solution. Partitioning and storage of water and solution can maximize deep percolation for ground water recharge and help soils withstand erosive forces.

Soil functions at multiple levels in the topo-sequence within agro-ecosystems are profoundly influenced by land use. In many areas, human pressure for production has modified land use and is causing unknown ecological effects. When adversely affected, the soil often turns dysfunctional in many respects. Several functions need to be maintained for ecological sustainability. These include water flow and retention, solute transport and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of potentially toxic materials, and maintenance of biodiversity and habitat.

Importance of infiltration rate in cultivated mountain soils

In mountainous areas of the HKH or the Indian Himalayan Region (IHR), where water is limiting in soil profile, changes in hydraulic properties within the surface layer can greatly affect the overall volume of water being infiltrated, stored, and redistributed within the upper soil profile/rooting zone during the rainy season. Therefore, improving infiltration and moisture retention, which is more important than the total rainfall, is very important given that a post rainy season dry spell can strongly depress crop yield (Araya et al., 2015).

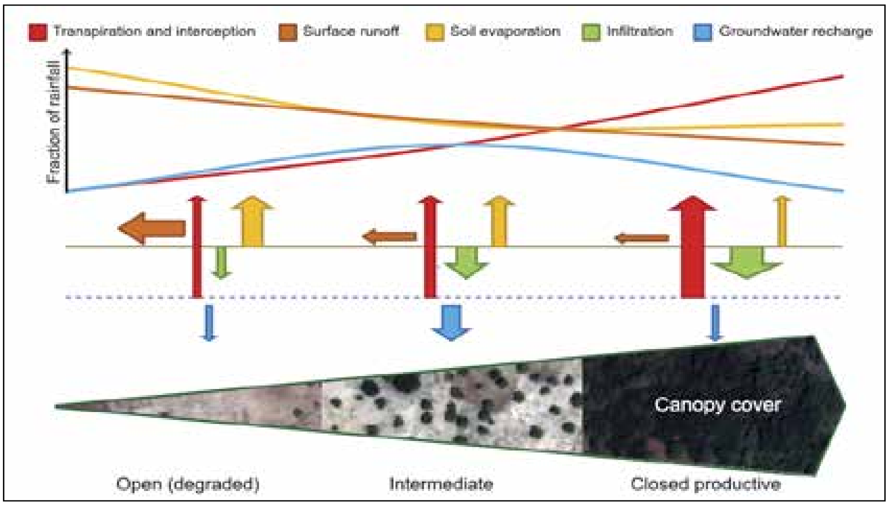
On sloping crop lands, the effects of growing plant vegetation (enhancing crop canopy cover) on infiltration, surface runoff, and evapotranspiration are key factors in determining the water content of soil, which ultimately impacts crop yield. Crops (erosion resisting legume crops) can also influence the macro-pore system, influencing the rate of infiltration (Barley, 1954). Increasing infiltration rates of sloping agricultural land not only affects water supply and precipitation transformations in soil directly, but also impacts erosion intensity. This is extremely important to the HKH region, where rainfall primarily occurs for three months a year, and soils left bare during these months are more fragile. Incorporating an actively growing crop during this period could protect the soil surface and increase water infiltration.

Splash erosion, caused by structural instability, leads to the formation of soil crust, which hampers the infiltration rate of soils and affects the germination of seeds. To ensure the optimum infiltration rate and better germination, it is important to prevent splash erosion and crusting. Wang et al., (2016) reported that straw mulch application decreased the mean splash loss by 68% compared to un-mulched soil in some of the studies. The mean basic infiltration rate (IR) measured, as an index of soil crusting, was 54% higher in soils with mulch cover than in soils without mulch.

Given that soils are the interface through which water infiltration occurs and that soil properties play a crucial role in this process, modifications to soil characteristics (soil erodibility) would change soil hydrological responses that may ease erosive processes (Cerdà, 1997). In conservation tillage systems, soils are generally reported to have a greater number of macro-pores and a greater continuity of vertically oriented macro-pores compared with conventional tillage (Wahl et al., 2004). Therefore, conservation tillage systems should enhance the infiltration capacity and reduce the runoff volume (Mwango et al., 2015). However, contrasting results have been reported on the impact of conservation tillage on soil physical properties and subsequent runoff rates. Several studies have shown that conservation tillage, such as zero tillage, results in equivalent or greater runoff than conventional till systems (Smith et al., 2007; Armand et al., 2009).

Importance of infiltration rate in forest ecosystem

Lack of experimental data reduces the prospect of establishing land use-stream flow relationships. There are very plausible explanations for this situation. Stream flow studies must be carried out on a drainage area basis. Many years of continuous, accurate records are required before acceptable results can be obtained for validating the hydrological models. High-yielding streams of superior water quality are universally associated with undisturbed forested land. This is because the soil structure and porosity are favourable to infiltration, maximum storage of water, and control of erosion. Yet this favourable influence of forests on water yield has repeatedly been questioned by hydrologists and water supply engineers on the ground that trees require more water for transpiration than do other plants, thus reducing the total amount of water that will be available on a watershed for stream flow. Obviously, both concepts are reasonable. One of the practical considerations in resolving this paradox is how to maintain favourable soil conditions and at the same time reduce transpiration draft. An optimum tree cover theory (Ilstedt et al., 2016) in which groundwater recharge is maximized at an intermediate tree density is depicted in Fig. 2. Below this optimal tree density the benefits from any additional trees on water percolation exceed their extra water use, leading to increased groundwater recharge, while above the optimum the opposite occurs.



Adapted from Ilstedt et al., (2016)

Figure 2: Optimum tree theory suggesting moderate tree cover maximises groundwater recharge.

Forests affect both water quality and quantity through a sponging effect, which helps in better infiltration and recharging of the ground water, gradually making it available during later stages of the lean season. Infiltration into forest soil is affected by soil cracks, soil texture and structure, root system and especially by surface humus which reduces the destructive effects of raindrops on soil surface and allows the outflow of air from pore space and the increase of infiltration intensity. In contrast, the layer of un-decomposed leaves, especially when they are compressed by snow or rain, can reduce entry of rainwater into the soil and increase surface runoff. Forest soils are characterized by very low compaction with relatively high porosity and water conductivity and contribute to the reduction of surface runoff and minimize the peak of storm flows. Oak forests have been reported to generate more water (307 m^3/day/km^2) without suspended material compared to agricultural land during the dry season and during monsoon. These forests generated low discharge (4874 m^3/day/km^2) coupled with minimum suspended load (0.06 t/day/cm^3) and dissolved load (0.40 t/day/cm^3) as compared to 8734 m^3/day/km^2 discharge, 1.6 t/day/cm^3 suspended load and 2 t/day/cm^3 dissolved load from agricultural land (Rawat 1998).

The litterfall added to the soil retains moisture, improves the soil structure thereby producing water stable aggregates which are not easily displaced by the water force. In the Himalayan region, the range of litterfall in different species varies from 4.2-7.7 t/ha/year (Chaturvedi 1983, Mehra et.al., 1985, Rawat and Singh 1989). Walsh and Voigt (1977) investigated the potential water retention capacity of beech litter compared with pine litter. The quotient of mean water retention capacity was 0.87 at beech litter and 0.54 at pine needle. In addition, in the thick layer of litter, especially in beech forests, a tendency for water to flow in temporal concentrated paths – which supported generation of funnel flow into the soil matrix – was observed. Following this process significant part of surface humus is excluded from the retention process, and therefore water retention is less than expected. Reduction of forest stand density leads to faster decomposition and mineralization of surface humus, which leads to changes in the form and thickness of surface humus (Homolák et al., 2017).

Campbell et al. (2004) studied infiltration processes by simulated rainfall on slope in the oak forest before and after the removal of surface humus. Significant difference was found only in the topsoil to the depth of 30 cm. The stems of young beech trees form direct infiltration paths, which allow easier infiltration of water from precipitation and stem flows. Presence of species also affects the rainfall portioning in the forest. Comparison between different forests in the lower Himalayan region indicated that between the low altitude oak (Quercus leucotrichophora) and pine (Pinus roxburghii) forest, canopy interception of pine is higher and that of oak is lower, which helps the later to absorb more water to grow and hence results in more infiltration (Negi et al. 1998). In the higher Himalaya, kharsu oak (Quercus semicarpifolia) is considered to be a better species that silver fir (Abies pindrow) (Pathak et al., 1983 and 1984; Mehra et.al., 1985; Loshali and Singh 1992; and Negi et.al., (1998).

Trees through their root system allow a definite volume of percolation and subsequent movement of percolated water. The roots also extract soil moisture regularly to provide necessary nutrients to super-structure above the ground. Thus, when forest is cut, this system gets snapped all of a sudden and thereby water gets stored into the soil profile and its subsequent utilisation or deposition by plant body gets disturbed. This results in sudden increase in water yield in the form of surface runoff. The results of experimental studies conducted in USA and elsewhere have shown increased stream flow following forest cutting in a watershed. In Japan and Kenya too, a large increase in water yield was observed following clearing of forests (Hibbert, 1965). It has been observed in some places that removing 30% or less of forest cover would not produce a significant change in stream-flow. In India, Subbarao et al. (1985) did not record any significant increase in fortnightly water yield after imposing 20% of forest thinning in a coppice sal (Shorea robusta) forest in Dehradun. It has also been observed that reforestation of a small brushwood watershed (1.45 ha) by Eucalyptus species (replacing brushwood) reduced water yield by 28%. Results of some such studies under Indian conditions are summarized in Table 2.

Table: 2. **Water yield as affected by land use**

Region/Place	Cover conditions	Runoff as % of rainfall	References
N-W Himalayas	Coppice sal forest	35-45	Lal and Subba Rao, 1981
	High sal forest	14-23	Mathur, 1980
	Untreated (Agril. Watershed)	9	Dhruvanarayana et al., 1985
	Treated (Agril. Watershed)	6	
	Grass cover	21-27 (monsoon)	Tejwani et al., 1975
Southern Hills	Forest watershed	4-11 (winter)	Chinnamanni, 1985
	Well managed (Agril. Watershed)	6-30	
	Ill managed (Agril. Watershed)	10-30	
	Grassland watershed	10-30	

The annual runoff (%) as that of annual rainfall from 2001 to 2009 in three nested watersheds – (i) 535 ha mixed with forest, grassland and agriculture, (ii) 105 ha with mixed Forest, and (iii) 267.5 ha with oak forest located at Almas watershed (Tehsil: Dhanulti; District : Tehri; State: Uttarakhand, India) was measured with the help of rectangular/ trapezoidal weir and water level recorder. Water yield from the 535 ha watershed varied from 0.70 percent to 22.6 percent as that of annual rainfall. The water yield from nested watershed of 105 varied from nil to 11.3 percent. The thick oak forest of 267.5 ha recorded water yield of 7.5 % to 41.3 % (Table 3). The variation was mainly due to the rainfall characteristics of each year, diversion of water by 65 mm underground pipe line for irrigation during the long gap between two successive storms (CSWCRTI Dehradun, 2000-2011).

Table: 3. **Monthly rainfall data and water yield of various watersheds at Almas watershed (Tehri Garhwal, Uttarakhand), CSWCRTI, Dehradun for the year 2000–2009.**

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009
Station No. 1 (Gharat, 535 ha mixed with forest, grassland and agriculture)									
Rain fall (mm)	857.2	1381.7	1555.2	1089.1	1399.6	871.2	1257.1	1225.7	1000.5
Water yield (% of rainfall)	3.7	22.6	09.3	10.08	14.2	1.12	9.4	17.9	0.70
Station No. 2 (Arikhal, 105 ha with mixed forest)									
Rain fall (mm)	857.2	1423.8	1407.1	1100.2	1399.6	871.2	1257.1	1225.7	1000.5
Water yield (% of rainfall)	00.8	4.4	1.2	1.95	10.1	0.00	0.00	11.3	0.17
Station No. 3 (Bharandanda, 267.5 ha with oak forest)									
Rain fall (mm)	857.2	1414.5	1713.5	1199.2	1352.4	1022.9	1419.2	1377.6	894.4
Water yield (% of rainfall)	41.3	16.0	18.8	31.51	34.9	11.73	14.89	19.8	7.5

Hydrological studies were conducted in three small watersheds with an area of 5.1, 5.7 and 19.8 ha under different management practices viz; with poor conservation measures (untreated), conservation measures (treated) and forest management, respectively to quantify the runoff, soil and nutrient losses. The results indicated that the land cover under perennial vegetation of shola forests reduced the runoff by 55% and land cover under annual crops with proper soil and water conservation measures reduced the runoff by 52.4% as compared to the untreated watershed without any conservation measures. The base flow component of total runoff was highest in the watershed under shola forest (73.6%), followed by the watershed treated with soil and water conservation (68.5%) and lowest under untreated watershed (3.19%).

A long term investigation (1956-88) conducted in 21 ha watershed in the Shiwalik region of Haryana State revealed that with the adoption of in situ soil water conservation techniques (trenching, brushwood/stone check dams, debris detention structures and water spreaders etc.) runoff reduced from 30 to 4 percent, peak discharge from 10 m^3/km^2 to zero in 32 years and sediment yield from 150 to 0.2 t/ ha due to development of dense vegetation (Table 4).

Table 4: **Reduction in runoff, outflow peak and sediment yield due to watershed management in Haryana Shiwalik**

Period/year		Rainfall (mm)	Runoff		Outflow peak (m^3/km^2)	Sediment yield (t/ha)
			mm	%		
Before 1956 (estimated)		1150.0	350.0	30.00	10.00	150.0
Actual	1964-65	1254.2	276.7	22.06	2.53	37.7
Actual (Average)	1965-70	1026.7	116.0	11.30	2.41	12.2
Actual (Average)	1975-79	1274.4	114.8	9.01	2.76	2.4
Actual (Average)	1979-84	1156.1	83.7	7.24	0.14	1.1
Actual (Average)	1984-88	828.2	35.1	4.23	–	0.2

Areas of the hilly region are generally susceptible to mass soil erosion and degradation problems caused by landslides, mine spoils and torrents. CSWCRTI, Dehradun has demonstrated that such highly degraded lands can be rehabilitated through bio-engineering measures. The nalota nala landslide project, Sahastradhara mine spoil rehabilitation project and Bainkhala torrent control project, Dehradun are examples of successful technology. The highly degraded mine spoil and landslide slopes were treated with small engineering structures such as loose stone/ gabion check dams, contour trenches, wattling, geo-jute etc. and planted with suitable vegetative species. The bioengineering technology not only rehabilitated the area but also improved the water and vegetation cover in the area on a sustained basis for use by the local people.

The rehabilitation measures in the landslide affected and mined watersheds (64 ha) rejuvenated water springs with sustained water yield even during the dry season, as depicted in Tables 5 and 6 (Sastry and Juyal, 1994; Juyal et al., 1998). The project was found to be economically viable in the long run as the rehabilitation efforts saved considerable funds that the State Public Works Department had to allocate for removing debris every year.

Table 5: **Effect of bioengineering measures on landslide stabilization in Nalota Nala watershed**

Description	Before treatment (1964)	After treatment (1994)
Runoff (mm)	55	38
Dry weather flow, days	100	250
Sediment load (Tonnes/ha/yr)	320	5.5
Vegetation cover (%)	<5	>95
Stream bed slope (%) Lower reach	12	7
- Middle reach	23	14
- Upper reach	54	44
Toe cutting	severe	nil

Table 6. **Impact of rehabilitation of mine-spoiled watershed at Sahastradhara in Dehradun**

Particulars	Before treatment (1983)	After treatment (1996)
Debris outflow (t/ha/yr)	550	8
Monsoon runoff (%)	57	37
Lean period flow (days)	60	240
Vegetation cover (%)	10	80

Research Needs

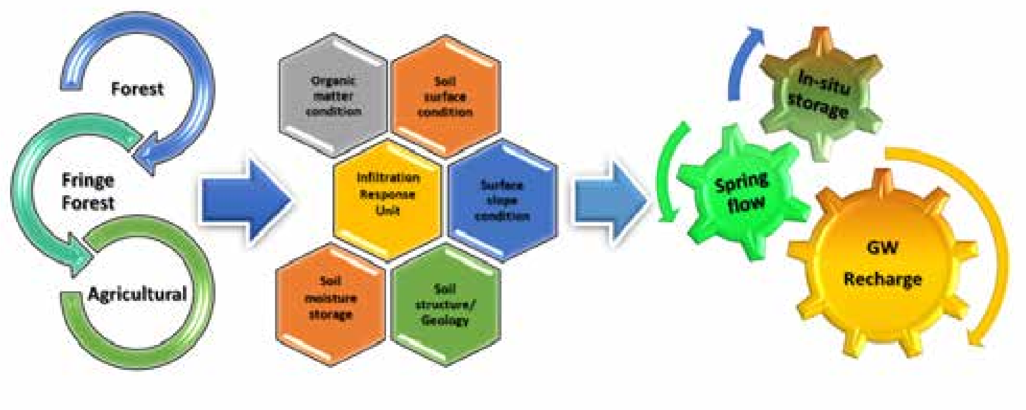
Hydrological footprints of resource conservation technologies (RCTs)

The ICAR-Indian Institute of Soil and Water Conservation (ICAR-IISWC) recommended conservation agriculture plus technology for rainfed sloping crop lands of the Himalaya in the context of steep slope, low soil infiltration rate and availability of limited amount of crop residues. Quanta of field experiments, conducted at this institute since its inception are mostly on resource conservation technologies (RCTs) in arable land; those include reducing soil loss beside *in-situ* conservation of soil moisture. The unerlying aim of the experiment was to increase the infiltration opportunity time, creating conducive soil surface conditions to improve infiltration capacity and augmenting recharge to the underground aquifers. The current database for various experiments could be very useful in objectifying the infiltration component of native to various RCTs employing the SCS curve number technique.

Mapping infiltration response units for groundwater recharge and spring flow augmentation

In the hilly terrains of the HKH, infiltration induced percolations suggests scope for spring flow. Since springs are a lifeline for hills, inducing spring discharge though watershed intervention such as soil and water conservation measures appropriate to different denominations of land parcel is the key to environmental protection. Further, such studies require development of *infiltration response units* (Fig. 3) that includes parameters such as i) organic matter condition, ii) surface condition/land use/land cover, iii) surface slope, iv) soil texture/structure and geology, and v) soil moisture storage. The complex contribution of these parameters individually or in combination, affects the provisioning of water services to the ecosystem. Since the surface runoff passes in a topo-sequence comprising forest to arable land through the fringe, the zone that augments maximum recharge to the surface spring should be identified as the most favourable.

Figure 3: Conceptual infiltration Response Unit in various land use parcel



Identifying most favourable tree species for recharge or spring rejuvenation

Surface humus plays a key role in mediating interactions between the atmosphere and soil. Its quantity, composition and origin of the individual components, internal structure and spatial distribution affect mainly water, heat, air retention and accumulation regime. Along with filtration, buffering, transformation and anti-erosion function, it defines the entire portfolio of ecological and environmental functions of soil. Different tree species in the IHR or the HKH have their own way of creating humus and preferential pathways in soil, especially along the interface of soil and root. There is a need to identify the properties of rhizosphere of various tree roots and soils from the perspectives of augmented infiltration rate and recharge contribution to spring.

Rainfall infiltration capacity for unsaturated slope

Rainfall infiltration rate depends on rainfall intensity as well as the water permeability coefficient and the hydraulic gradient of topsoil. Both the water permeability coefficient and hydraulic gradient vary throughout the infiltration process due to the variations of negative pore-water pressure in the soil. The initial pore-water distribution is an essential input for transient flow analyses in unsaturated soils. Previous studies indicate that the antecedent infiltration rate not only has a significant influence on the initial pore-water distribution and hence on the pore-water pressure redistribution as a result of subsequent rainfall infiltration, but also leads to a change in the water permeability coefficient of the soil (Rahimi et al., 2011). Main factors, influencing rainfall infiltration of an unsaturated slope, include geologic and geomorphic features, slope characteristics, precipitation, and evaporation. The properties of slope itself are the internal factors, and the key is permeability of rock and soil. In the HKH region, the other controlling features of infiltration are structural morphology, dip and strike of bedding and fracture plane and lineaments from a geological point of view.

Forest and water relationships under conditions of controlled silvicultural management and uncontrolled deforestation due to logging or forest fire

A comprehensive study is required to establish fundamental forest and water relationships by furnishing coefficients of runoff, infiltration, and water storage for different types of land use such as grazed land, forests of different density, agricultural lands. Considering the theory of optimum forest species, there is a need to develop principles of silvicultural management that will ensure maximum supply of usable water of highest quality. Studies on riparian forest management, sequential land use change effects on infiltration and perennial nature of springs should be conducted to work out feasible and practical methods of stabilizing soil in logging operations, on road banks, and along streams and reservoir shore lines.

Forests in the HKH region are subject to forest fire. Controlled forest fire has some positive effects but uncontrolled forest fire causes loss of canopy cover, disturbs the hydrological flux balance, and increases surface runoff. Hydrophobic soils are formed when hydrocarbon residue is created after organic material is burnt and soaks into empty pore spaces in the soils, making it impervious to water and inducing runoff.

Creating databases of water spring health

The HKH has a lot of spring sources that are essential to mountain living. Often parameters responsible for good spring health source are complex and difficult to identify. Therefore, there is a need to map these spring sources and document pertinent and perceived parameters responsible for better health in line with the health card of soil. Once spring sources are mapped, various niche modelling approaches can be adopted to find the most important factors responsible for good spring health and focused interventions could be adopted to improve those factors.

Interventions to manage infiltration and recharge

The popular 3R technique (recharge, retention and re-use) is universal and integral to managing water infiltration to soil in any ecological situation including the mountain ecosystems. The institutions in the HKH region have a plethora of SWC technologies that can be up-scaled for infiltration management in various land use systems while also arresting land degradation. Given the importance of issues of water management in the IHR and the HKH, these technologies can be further tweaked to make them more amenable to effective resource use besides providing various ecological services.

Often storage is associated with large surface reservoirs and mega-dams. 3R presents an alternative concept of using many smaller systems and storing water in the landscape. Much water storage is invisible as it takes place in the ground, in the unsaturated zone of the soil, and appears as a spring source. In addition, water can be stored in many small surface systems.

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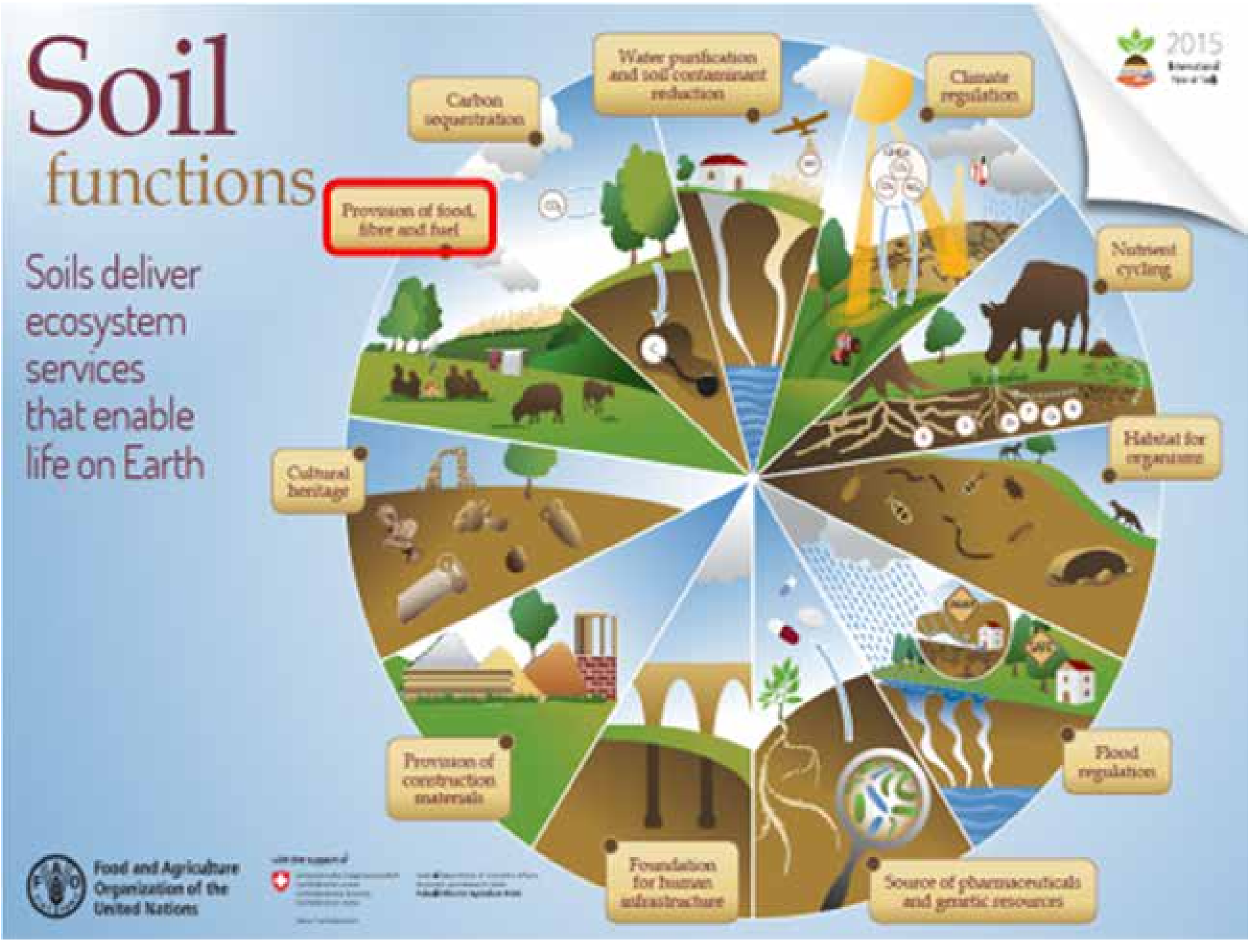
Theme: Climatic variability in soil management

Preparing soil function for climate change adaptation and mitigation

Soils help to combat and adapt to climate change by playing a key role in the carbon cycle



Review of status of soil organic carbon (SOC) and other nutrients in Hindu Kush Himalaya

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Abstract

Global warming, one of the burning issues today, is increasing due to release of carbon into the atmosphere. Soils host the largest terrestrial carbon pool, which is playing a crucial role in the global carbon balance. The Hindu Kush Himalayan (HKH) region spans over 4 million km2, which is about 2.9% of the global land area and approximately 18% of the global mountain area; the region comprises a 3,500 km long, complex landscape. The HKH region plays a huge role in preventing climate change while also contributing to the livelihood of local people. The role of soil properties and SOC in the climate system (especially in the context of climate change adaptation and mitigation) has become recognized only in recent decades. Data across the HKH countries vary both in terms of spatial representation and temporal resolution. Thus, there is strong scope for exploring the impacts of topography, climatic conditions and land management interventions on soil formation, SOC contents and their relation to climate change and the livelihood of people. Besides this, the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development identified the need to restore degraded soils and improve soil health. Building a coherent and consistent regional database on SOC and other nutrients in the HKH region will be a key task for ICIMOD in the near future.

Background

Global warming is increasing due to release of carbon into the atmosphere. Soils host the largest terrestrial carbon pool (Scharlemann et al., 2014) and play a crucial role in the global carbon balance (Lal, 2013). Soil organic carbon (SOC) stocks amount to an estimated 1,500 ±230 GtC in the first metre depth of global soils, nearly twice as much as atmospheric carbon (828 GtC as CO2) (Le Quéré et al, 2016). This phenomenal SOC reservoir is not static, but is constantly cycling between the different global carbon pools in various molecular forms (Kane, 2015), viz., atmospheric carbon, plant materials and SOC in the nutrient cycling. Regarding spatial distribution of land in the global context, mountains occupy 24% of the global land area, i.e., about 25 million km2, and are home to 12% of the world's population (GTOS, 2008). The Hindu Kush Himalayan (HKH) region spans over 4 million km2, which is about 2.9% of the global land area and approximately 18% of the global mountain area; the region covers a 3,500 km long, complex landscape. Politically, the region comprises all or parts of eight countries: Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. The HKH region plays a huge role in preventing climate change while also contributing to the livelihood of local people.

Intensification of agricultural practices and land use has resulted in a decline in the content of organic matter content in soils (Galloway et al., 2008). Although the role of soil properties and SOC in the climate system and in the context of climate change adaptation and mitigation has become recognized only in recent decades, it has been validated by various studies, both experimentally and through modelling (Lal, 2013). The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development identified the need to restore degraded soils and improve soil health (FAO, 2017). Apart from this, substantial progress has been made in recent years towards building a deeper understanding of the processes controlling soil C storage. However, FAO and ITPS (2015) state that many gaps remain in our knowledge and there is need for further research on the subject.

Rationale

It is essential to have an improved understanding of the soil function in biophysical processes. However, data are very limited in the HKH region to provide a basis for effective biodiversity conservation and management. Trend analysis and inputs for models that simulate climate, hydrology, glaciology, and the like require more data, of greater resolution, and over the longer term than currently available data. So this study aims to review and document the assessment of SOC and other soil macro-nutrients in the region by country and time domain.

The objective of the study was to review the SOC and other soil nutrients in the HKH region.

Methodology

The study was conducted primarily as a rapid desk review of relevant literature. It was followed by documentation and analysis of data, information and methods described in the literature. Finally, the data was interpreted and a report was prepared. The report will serve as a reference for stock taking of SOC and soil nutrients in the RMCs.

Soil type and land use across HKH regional countries

In the literature reviewed during this study, soil types available in the different regions and their land use classifications have been analysed and tabulated as follows. Latest data available have been taken into account for developing this database.

Most areas in the HKH are found to be composed of alluvial soil of various types with some areas facing the threat of desertification. India has the largest alluvial land followed by the other countries except Afghanistan, which is affected by desertification, and China, which has very limited arable soil. Currently available data suggests that the HKH region severely lacks documentation of types of soil available and also their coverage. There is limited information on the soil type. However, soil types in the region were tabulated based on available studies (See Table 1).

Table 1: **Soil types in the HKH countries**

Countries	Available soil types
Afghanistan	Arid Deserted soil Desertification affects 75% of total area
Bangladesh	Alluvial (northeast, east, south and southeast) Degraded lateritic and alluvial (Southwest) Rest parts with lateritic and pedocalic including alluvial
Bhutan	Tethyanmetasediments in the High Himalayas Quaternary Alluvium in the southern foothills ≈ 27% of soils are Cambisols (mid altitude) or Fluvisols (southern belts) ≈ 45% of soils are acrisols, ferralsols and podzols ≈ 21% of soils are lithosols on steep slopes A few areas with non-volcanic andosols
China	Very limited arable soil (121.7 million hectares) which is only 40% of global average Only one-third of arable soil is fertile Rest are low or middle low arable soil
India	Alluvial (100,006,000 ha) (30.4%) Coastal alluvial (10,049,000 ha) (3.1%) Red soil (87,989 ha) (26.8) Laterites (18,094,000 ha) (5.5%) Black soil (54,682,000 ha) (16.6%) Brown forest soil (540,000 ha) (0.2%) The rest soil includes hill, Terai, mountain meadows and desert)
Myanmar	Alluvial in low lands (silt and clay) Total cultivable land area of 18,008,511 ha(5.3%) of which 10% is vulnerable to soil erosion of this about 299,467 ha are acid sulphate soils, degraded soils, peat soils, and swampy soils Saline and alkaline soils accounts for 659637 ha
Nepal	Agricultural soil 23 % to 28% of the total Pasture soil 1,701,668 ha of which 1,082,232 ha (66.6 %) is located in the mountains, 74,101 ha (4.35 %) in the middle hills and 545,335 (32.05 %) ha in the hills
Pakistan	Literatures on soil types not found

Lowlands were found to have alluvial soil and the highlands were found to have laterites and degraded soil types. Areas which lack low rainfall and less weathering of soil were found to have arid soils.

Similar to data on soil types, country-wise data on land use classification is not uniform and doesn't allow comparison. There is a need for properly classified and uniform data on land use classification in the entire HKH region. The land use land cover of 2010 in the HKH has been reviewed (See Table 2).

Table 2: **Country wise land use classification in the HKH (in sq.km)**

Land use	Afghanistan	Bangladesh	Bhutan	China	India	Myanmar	Nepal	Pakistan
Agricultural	78997	4049	1208	457	14002	6712	43910	20945
Grassland/Pasture	295095	0	1995	2429	1015	0	11634	40619
Forest	13710	9081	26748	4051	7007	39143	57538	21517
Barren	243518	582	1865	0	1678	0	15678	73371
Urban	326	954	68	300	0	54	469	0
Water bodies	21218	0	144	309	0	197	882	1073
Fallow	652864	5	0	0	1575	0	0	0
Waste area		50	0	707	1286	0	0	0
Shrub land		6630	3864	475	0	96	5008	0
Dry land		0	0	3227	0	0	0	0
Wooded land		0	0	0	0	8931	0	0
Other land		0	2994	0	0	374	12062	23763
	1,305,728	21,351	38,886	11,955	26,563	55,507	147,181	181,288

Soil organic carbon contributes to climate change mitigation

Data on soil organic carbon (SOC) obtained from various sources have been compiled and tabulated for comparative analysis. Myanmar and Afghanistan lack studies on SOC (if studies have been conducted, they have not been documented). Also, the units used for measuring SOC are not uniform across countries, which makes it difficult to compare and analyse the results.

FAO/GSP (2017) has documented SOC contents in the areas in order to map output. Table 4 shows the average SOC content in the HKH countries whereas Table 1 shows the country level studies on types of soil available in the HKH.

Table 3: **SOC overview of member countries across the HKH region**

Country	SOC	
	Highest	Lowest
Afghanistan	–	–
Bangladesh	1.15%	0.36%
Bhutan	59%	34%
China	45%	9%
India	18.31 Pg	2.24 Pg
Myanmar	–	–
Nepal	4%	0.1%
Pakistan	1.06%	0.81%

Table 4: **SOC values by country (mg/ha)**

SN	Country	MIN	MAX	RANGE	MEAN	STD
1	Afghanistan	0	121	121	34	14
2	Bangladesh	26	597	571	82	29
3	Bhutan	0	315	315	86	39
4	China	24	263	239	57	20
5	India	12	225	214	40	8
6	Myanmar	24	183	159	55	9
7	Nepal	12	199	187	61	58
8	Pakistan	2	249	247	39	12

Source: FAO/GSP (2017)

Soil productivity contributes to food security and livelihoods

Among all the countries, Nepal had available data not only on all the major nutrients but also on micro nutrients, as shown in Table 5. Afghanistan did not have any properly documented data on soil nutrients. Pakistan only had a small amount of data on phosphorous and that too was confined to a district named Layyah. The review found a severe lack of soil nutrient data from the HKH region. The limited data available, too, is mostly outdated. Table 5 provides the findings on major soil nutrients in the HKH countries.

Table 5: **Soil nutrient variation in different countries of HKH region**

Country	pH	N	P	K
Afghanistan	–	–	–	–
Bangladesh	6.60 - 7.06	0.08 - 0.52%		
Bhutan	5.3 - 6.9	736.6 - 3789.4	280.3 - 506.8 (as P2O5)	96.8 - 504.7
China	–		18.8 mg/kg	119.08 mg/kg
India	–	1.67	1.46	2.17
Myanmar	4 - 8.5	–	–	–
Nepal	5.75	0.19 %	72 mg/kg	136 mg/kg
Pakistan	–	–	–	–

Discussion

SOC and other nutrients in the soils are affected by different prevailing factors such as land use/land cover changes, land management practices of agricultural and forest lands, environmental factors including climate and topography (Sitaula et al., 2004). Thus, while studying the SOC and soil nutrients in the region, we should also focus on land use pattern, land management and interventions, viz., sustainable soil management practices (SSMP) through interventions such as farmyard manure (FYM) and bio-char, which helps maintain the alkaline and acidic properties of agricultural soils. Climatic and topographic factors also determine the SOC and nutrient levels. Topographic complexities play a significant role given the diverse topography of the HKH.

Lowlands, valleys and mountain terrains have varied levels of SOC and other soil nutrients due to the slope factors which specifically control soil deposits and ultimately affect SOC sequestration in the soil profile. The arid nature of soil in Tibet, Afghanistan and parts of Pakistan and terrain conditions in Nepal, Bhutan and parts of India are affecting the accumulation of SOC and nutrients in soil.

Conclusion and recommendations

- There is growing recognition of soil's contribution toward mitigating climate change impacts and ensuring the food security and livelihood of local communities. Thus, there is strong scope for exploring the impacts of topography, climatic conditions and land management interventions on soil formation, SOC contents and their relationship with climate change and people's livelihoods.
- Scope for database creation: There is scope for building a comprehensive regional database on soil organic carbon and other nutrient constituents in ICIMOD's member countries .
- Filling the gaps: Work is needed to fill the gaps in data collection through field campaigns on SOC and other nutrients in the regional member countries.

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Digital soil mapping of soil organic carbon stock in Bhutan

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Abstract

Soil organic carbon (SOC) plays an integral part in improving soil security, water security, food security, energy security, climate change abatement, biodiversity protection, and ecosystem services. As such, it is important to understand its stock and spatial distribution for better management. However, not many countries have managed to map their national SOC stock and Bhutan is no exception. The paucity of SOC information makes it difficult to formulate effective plans and programmes to increase C sequestration and enhance SOC storage in the country. In this regard, a preliminary mapping of SOC stock of Bhutan for the top 30 cm depth was carried out to establish baseline information and contribute to global SOC mapping. A total of 993 data points were used for mapping SOC stock using regression kriging (RK). Regression tree model (RTM) and ordinary kriging were used to perform the RK with elevation (DEM), land use land cover (LULC), slope, aspect, profile and plan curvatures, normalized difference vegetation index (NDVI), SAGA wetness index (SWI), mean precipitation, mean temperature, geology, and terrain ruggedness index (TRI) as environmental covariates. The model validation was done by repeated data splitting method. The preliminary results show that for the top 30 cm depth, Bhutan stores about 0.4 GtC with SOC density ranging from 0.5 to 315.3 tonnes ha^{-1}. Among the environmental covariates, LULC, topography, and climatic factors had significant influence on the SOC stock and its spatial distribution. As expected, SOC stock was relatively low in the southern and eastern regions as opposed to the western and northern parts of the country. Under different LULC types, the SOC stock was lowest under agricultural land and highest under forest, as anticipated. Although Bhutan stores only about 0.1% of the global SOC stock (0-30cm depth), its contribution in terms of its total area is more than five times. However, this preliminary assessment is based on a small dataset and may not be very accurate. In order to have a more reliable SOC stock estimation with less uncertainty, more soil information will be required. Further, proper strategies for C sequestration and land management will be required to reduce C emission and enhance C sequestration.

Introduction

Soil is essentially made up of minerals, organic matter/carbon, water, and air. Among these four main components, soil organic carbon (SOC) forms the integral part of functional soil. This is largely because SOC has the ability to improve the soil physical, chemical, and biological properties, which can enhance soil security. Enhanced soil security can improve food security, water security, energy security, climate stability, biodiversity, and ecosystem services (McBratney et al., 2014). SOC also plays a key role in global carbon (C) cycle as it is the largest terrestrial C pool. Because of the important role it plays, SOC is often considered as a common indicator for soil security, water security, and ecosystem services. Further, SOC stock is one of the three indicators in assessing Land Degradation Neutrality (LDN) status by 2030. Bhutan being an LDN member country, information on SOC stock and its spatial distribution will be vital for assessing its LDN status by 2030.

Globally, soil stores about 1,500 GtC (1 GtC = 10^{15}gC) in the top one meter (Jobbágy and Jackson, 2000) which is approximately three times as much C found in the biosphere and twice as much C found in the atmosphere. For the top 30 cm depth, it stores about 680 GtC. Assuming that other components of global C cycle remain constant, a change in global SOC storage by 1% may trigger a shift of about 8 ppm of CO_2 concentration in the atmosphere. This highlights the significance of C sequestration and storage in the soil in climate change mitigation. In order to enhance C sequestration and C storage, adequate information on SOC is necessary to formulate appropriate land management and C sequestration strategies. However, such information is limited in most of the countries, particularly in developing countries. This has posed a challenge in enhancing soil quality, increasing resilience to climate change, and ensuring continuous ecosystem services through better SOC management.

To this end, the National Soil Services Centre (NSSC) under the Ministry of Agriculture and Forests made its first attempt to produce the SOC stock map of Bhutan for the top 30 cm depth with 993 observed data using digital soil mapping (DSM) techniques. The DSM of SOC stock of Bhutan was done to: i) contribute to global SOC stock mapping initiated by Global Soil Partnership (GSP); ii) set up a national baseline information on SOC stock; iii) help to formulate better C sequestration and SOC management strategies, and iv) build the capacity of the national staff on DSM.

Materials and method

Study area

Bhutan is a landlocked country located in the Himalayas with China in the north and India in the east, west, and south. It has a geographical area of 38,394 km2 with rugged terrain characterized by 'V' shaped valleys and high peaks. The valleys are characterized by narrow alluvial floors, fans, and terraces, with the lower slopes and alluvia often mantled with colluvia from upslope and aeolian deposits (Baillie et al., 2004; Caspari et al., 2006; Dorji et al., 2009). Within less than 200 km (south-north), the altitudinal gradient increases from about 97 to about 7,570 metres above sea level (masl). As such, there exists several agro-ecological zones with distinct climatic regimes in between. Monsoon dominates the climatic condition with annual precipitation varying from more than 2,000 mm in the south to less than 1,000 mm in the north and central parts of the country. The mean annual temperature ranges from approximately 14° to 26° C during summer to about -3° and 15°C in winter.

The Himalayan mountains are young and still rising, leading to landscape dissection and natural soil erosion (Singh et al., 2010); the latter process is continually affecting soil development. Soil zones are grouped under four categories based on altitude: i) moderately weathered and leached thin dark topsoil over bright subsoil up to about 3,000 masl; ii) very bright orange-coloured non-volcanic andosolic soils and iii) acidic soils with thick surface litter that grade to weak podzols up to about 4,000 masl; and iv) alpine turf with deep dark and friable topsoil over yellowish subsoil mixed with raw glacial deposits above 4,000 masl (Baillie et al., 2004).

More than 58% of Bhutan's population depends on agriculture, livestock and forestry for their livelihood. However, the cultivated agricultural land accounts only for about 3% of the total land area (LCMP, 2010) due to rugged terrain and extreme climatic conditions. As such, more than 70% of the total agricultural land is located on steep slopes with high incidence of soil erosion. On the other hand, about 71% of the country is under forest cover (LCMP, 2010) with very rich biodiversity. As expected, the spatial variation of different LULC types is greatly influenced by altitude, slope, and climatic regimes. Hence, broadleaf forest is predominant below 2,500 masl with coniferous forest between 2,500 and 3,500 masl. However, shrubs and grassland occur all along the altitudinal gradient. As anticipated, snow and screes are largely confined to areas above 3,500 masl. Conversely, agricultural land is mostly located on valley bottoms and mountain foot slopes.

Soil data

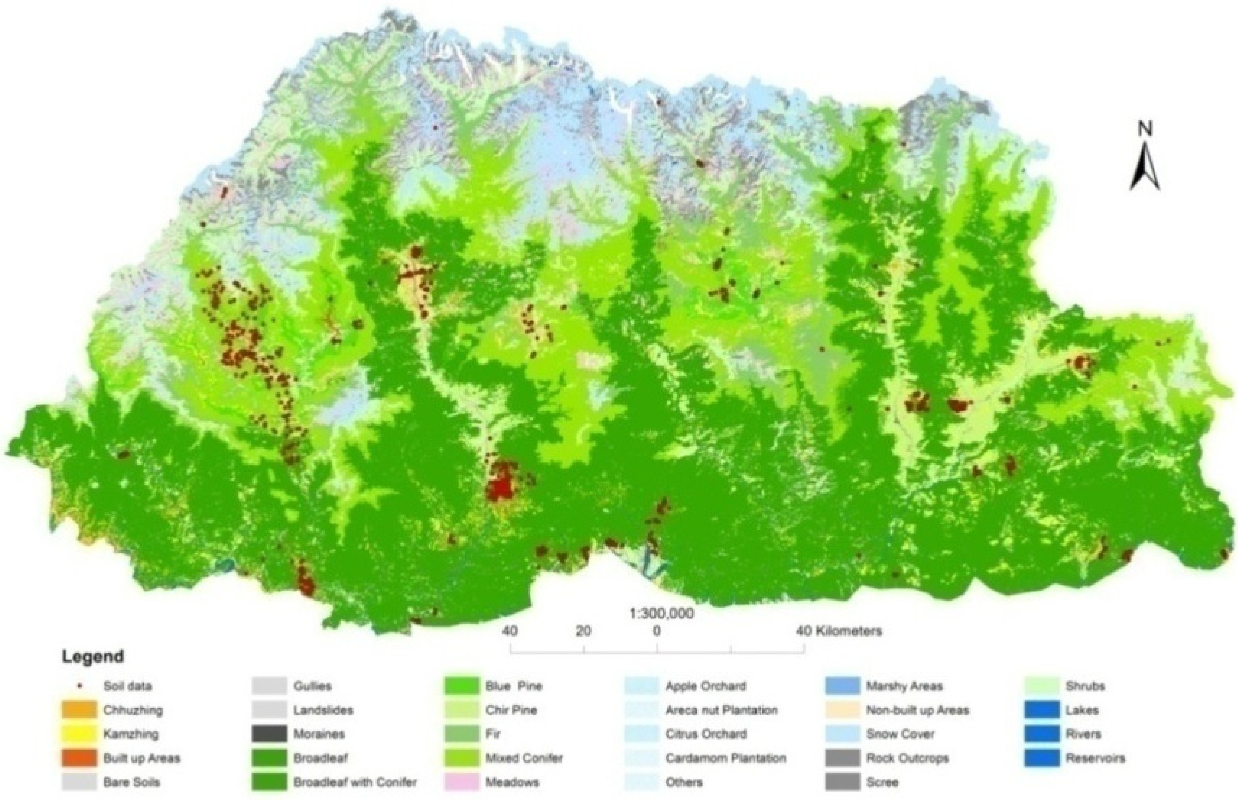
Soil information in Bhutan is limited as not many soil surveys have been done. Bhutan's soil resources remain unexplored and poorly documented. For this SOC mapping exercise, a total of 993 data points from previous soil surveys (1997-2017) were used (Fig. 1). About 80% of the total data points were from soil profile pits while the remaining data points were from auger bore holes. Soils were described and sampled based on genetic horizons. Samples were analysed for various soil parameters including carbon (C) concentration using Walkley and Black (1934) and bulk density using the core ring method (Blake et al., 1986).

Since soil samples were collected based on genetic horizons, they had different soil depths and this posed a challenge in digitally mapping SOC stock for a given soil depth. In this regard, an equal-area spline function was fitted to the profile values of the target soil variables using the CSIRO Spline Tool V2 (ASRIS, 2011) to convert the horizon-based values to the desired soil depth (0–30 cm). The equal-area spline function is based on the quadratic spline model of Bishop et al. (1999).

Acquisition and derivation of environmental covariates

Digital Soil Mapping (DSM) of any soil property hinges on the use of easily discernable ancillary soil and/or environmental attributes. To generate the terrain attributes, a 30m DEM covering the whole of Bhutan was extracted from the Shuttle Radar Topography Mission (SRTM) elevation data portal (http://earthexplorer.usgs.gov) and was re-sampled to 1 km resolution. Slope gradient, aspect, slope curvatures (profile and plan), SAGA wetness index

Figure 1: Distribution of soil observation sites



(SWI), and terrain ruggedness index (TRI) were derived from the DEM using the System for Automated Geo-scientific Analysis (SAGA) software (http://www.saga-gis.org/en/index.html) and Arc GIS software (version 10.3). In addition to the above covariates, the LULC data (LCMP, 2010), geological map (Department of Geology and Mines), mean temperature and precipitation (www.worldclim.org), and normalized difference vegetation index were used as covariates after re-sampling them to 1 km resolution.

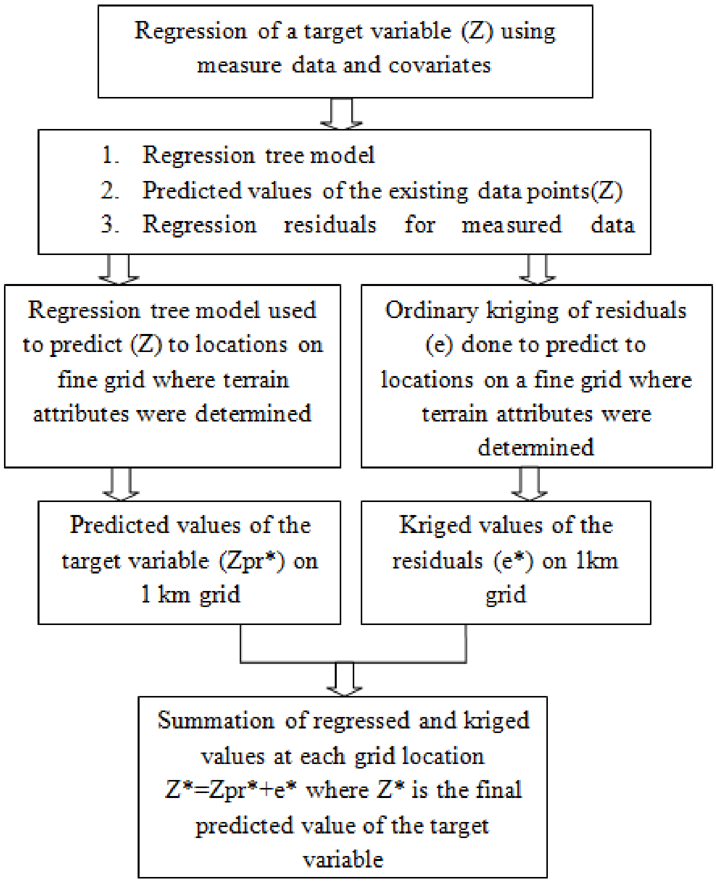
Spatial modelling of SOC concentration and bulk density

Digital Soil Mapping (DSM) of any soil property is done with the assumption that a soil property of interest is closely associated with easily discernible ancillary environmental variables. This enables the target variable to be predicted by establishing relationships between it and the ancillary variables (McBratney et al., 2003). Based on this assumption, several methods have been used to digitally map the target variable. Odeh et al. (1995) compared several methods of DSM: multi-linear regression, ordinary kriging, universal kriging, isotopic co-kriging, heterotopic co-kriging, and some variants of regression kriging (RK) models, and found the RK model to be most superior. A later study reported the RK model to be more practical and robust than other prediction models (Minasny and McBratney, 2007). As such, we used RK to digitally map the SOC stock.

RK has two main components i.e., regression and kriging (Fig. 2). For the regression part, the regression tree model (RTM) was used (Cubist 2.09 package) with elevation (DEM), LULC, slope, aspect, profile and plan curvatures, NDVI, SWI, mean precipitation, mean temperature, geology, and TRI as covariates to predict the target variable. The RTM is found to be robust and appropriate for complex landscapes, such as in the Himalayas. The RTM is a non-parametric prediction model, which predicts the target variable based on linear regression models instead of discrete values predicted by the classical tree models (Minasny and McBratney, 2008).

At each node of the tree model, conventional linear least-squares regression is used to create the model associated with each of the terminal rules. Thus, the model generates a set of comprehensible rules, each of which has an associated multivariate linear model. When the rule conditions are met, the model predicts the target variable for each grid cell that has values for the appropriate predictor covariates (Minasny and McBratney, 2008). For the kriging part, the residuals, which are the difference between the measured and regressed values, were interpolated onto the entire 1 km grid, using a simple kriging, embedded in the package: Variogram Estimation and Spatial Prediction plus Error (VESPER) (Minasny et al., 2005). The final predicted value of the target variable at each 1 km grid cell was computed by summing up the regressed value from the RTM and the kriged residual (Fig. 2).

Figure 2: Flow chart showing the RK steps for DSM



Aadapted from Odeh et al. (1995).

Data validation

Any prediction model needs to be validated to assess its accuracy and reliability. It can be done either through external or internal validation. The former uses a new validation dataset from the same or similar population for validating previous models and is considered to be relatively better than internal validation methods. However, given the difficulty in obtaining a new independent external dataset, it becomes necessary to opt for internal validation.. Repeated data splitting is a common internal validation method and we used this to validate our models. The whole data was divided into two portions, called the training and validation datasets. The training dataset constituted 70% of the total data points (698 points) and was selected through a simple random sampling procedure. The remaining 30% data was used as a validation dataset. Firstly, RTM was fitted onto the training dataset (using Cubist 2.09) and the model was used to predict the target variable for the validation dataset. Secondly, the residuals for the training dataset were calculated by subtracting the regressed values from the measured values of the target variable. Thirdly, the residuals of the training dataset were kriged to predict the residuals of the validation dataset using VESPER. The final RK prediction for the validation dataset was obtained by summing the regressed values from RTM and kriged values (Fig. 2). The performance of the RK model was assessed by plotting the predicted values with measured values of the validation dataset. The whole process was repeated ten times to assess the stability of the prediction accuracy of the RK model. At each iteration, the statistical parameters including: (i) root mean square error (RMSE), (ii) coefficient of correlation (R), (iii) coefficient of determination (R^2), and (iv) mean error (ME) were determined and averaged at the end to provide the overall prediction accuracy of the model.

Computing SOC stock

Although SOC density and SOC stock are often used interchangeably in literature (Minasny et al., 2006), they differ in scale and unit. SOC density is the SOC mass per unit area for a given depth, which can be calculated as:

$$SOC_d\ (kg\ m^{-2}) = SOC\ (kg/kg) * BD\ (kg\ m^{-3}) * D(m) \qquad (1)$$

where SOC density (kg m^{-2}), is SOC concentration (kg/kg), is bulk density (kg m^{-3}) and is depth interval thickness (m). On the other hand, SOC stock is the actual SOC mass for a given soil depth and area. It was calculated by summing up the product of SOC density and area of the smallest mapping unit e.g., grid cell 1 × 1 km^2.

$$SOC_{st}\ (t) = \sum_{i=1}^{n} \{(SOC_{di} * A_i)/10^3\} \qquad (2)$$

where SOC stock in metric tonne, is number of 1 km grid cells, is SOC density of grid cell for a particular depth interval (kg m^{-2}), is an area of 1 km grid cell (1km^2) and is the unit conversion factor.

Results and discussion

Spatial modelling of SOC concentration and bulk density

As shown in Table 1, the RTM based on the whole dataset (993 data) used MT, GEO, NDVI, PLCUR, SLOPE, ASP, MP, and ALT as conditions to perform the regression for SOC concentration. However, MP, MT, ALT, NDVI, TRI, SLOPE, ASP, SWI, PLCUR, and PRCUR were used as covariates to predict the SOC concentration. Similarly for bulk density, MP, ALT, SWI, MT, PRCUR, NDVI and ASP were used as conditions and MT, MP, ALT, NDVI, TRI, SWI, SLOPE, PRCUR, PLCUR, and ASP as covariates. Among the environmental covariates, MP, MT, ALT, and NDVI showed more influence on both SOC concentration and bulk density, and their spatial distributions.

Table 1: **Usage (%) of covariates in the RTM for predicting SOC and bulk density**

Attribute usage	SOC Concentration (0-30 cm depth)			
Conditions (Usage in %)	MT (99%)	GEO (72%)	NDVI (43%)	PLCUR (32%)
	SLOPE (25%)	ASP (24%)	MP (13%)	ALT (9%)
Environmental covariates used in regression tree model (Usage in %)	MP (89%)	MT (86%)	ALT (70%)	NDVI (60%)
	TRI (57%)	SLOPE (48%)	ASP (46%)	SWI (41%)
	PLCUR (14%)	PRCUR (11%)		
Attribute usage	Bulk density			
Conditions (Usage in %)	MP (75%)	ALT (49%)	SWI (45%)	MT (32%)
	PRCUR (12%)	NDVI (9%)	ASP (8%)	
Environmental covariates used in regression tree model (Usage in %)	MT (99%)	MP (95%)	ALT (91%)	NDVI (81%)
	TRI (74%)	SWI (67%)	SLOPE (62%)	PRCUR (31%)
	PLCUR (20%)	ASP (13%)		

TRI = terrain ruggedness index, SWI = SAGA wetness index, NDVI = normalized difference vegetation index, MT = mean temperature, MP = mean precipitation, ASP = aspect, PLCUR = plain curvature, PRCUR = profile curvature, ALT = altitude.

Overall, the RTM performed well, as indicated by the low average error, and ME for both SOC concentration and bulk density (Table 2). The average error was 0.89 g/100 g for SOC stock and 0.05 g cm^{-3} for bulk density. The relative errors of both SOC stock and bulk density were less than 1. The coefficient of determination (R^2) was 0.59 for SOC concentration and 0.88 for bulk density. The RMSE for SOC and bulk density was 1.34 and 0.09 g cm^{-3}, respectively. Looking at the ME, the RTM was less biased in predicting bulk density than SOC concentration as its values were much closer to zero.

Table 2: **Performance of RTM in predicting SOC concentration and bulk density**

Depth (cm)	SOC (g/100g)					Bulk density (g cm^{-3})				
	AE	RE	ME	RMSE	R^2	AE	RE	ME	RMSE	R^2
0 – 30	0.89	0.61	0.05	1.31	0.59	0.05	0.23	0.0002	0.09	0.92

SOC = soil organic carbon, AE = average error, RE = relative error, ME = mean error, RMSE = root mean square error, R = correlation coefficient, R^2 = coefficient of determination

Validation of RK model

Judging by the statistical parameters (Table 3), based on ten iterations, the overall RK prediction for SOC concentration is good with mean R^2 of 0.67. The average RMSE is also low (1.23g/100g) with ME close to zero (0.02), indicating that RK is less biased.

Table 3: **Performance of RK in predicting SOC concentration**

Depth (cm)	SOC (g/100g)		
	ME	RMSE	R^2
0 - 30	0.02	1.23	0.67

ME = mean error, RMSE = root mean square error, R^2 = coefficient of determination

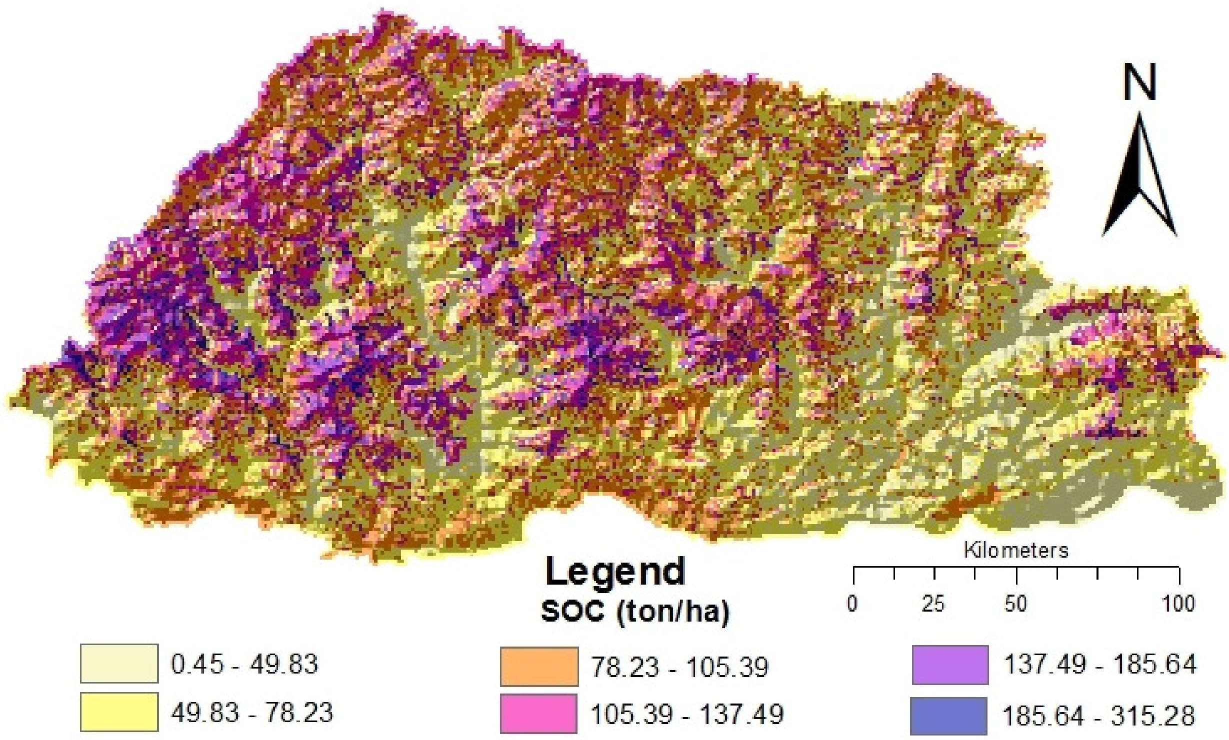
SOC density under different LULC types

SOC density for each 1×1 km^2 grid was computed using the RK predicted SOC concentration and bulk density values for the top 30 cm depth (Eq. 1). The spatial variation of SOC density was greatly influenced by LULC, which is directly controlled by the climate and topography of the study area. Under different LULC types, the mean SOC density for the upper 30 cm depth decreased in the order of mixed conifer forest> fir forest> others> grassland> shrub land> blue pine forest> marshy land> horticulture> dry land> paddy land> built-up areas> chirpine forest (Table 4). Similarly, the effect of topography was also very clear with low SOC density on the valley bottoms and lower mountain slopes as opposed to higher SOC density on the upper slopes. This is in line with the results reported by Dorji et al. (2014).

Table 4: **Predicted SOC density under different LULC types (0-30 cm depth)**

Sl #	LULC type	Mean SOC (t/ha)	Sl#	LULC type	Mean SOC (t/ha)	Sl#	LULC type	Mean SOC (t/ha)
1	Paddy land	62.16	6	Blue Pine Forest	84.79	11	Horticulture	71.58
2	Dry land	64.05	7	Chir Pine Forest	51.54	12	Marshy Area	74.1
3	Built Up Areas	60.52	8	Fir Forest	102.35	13	Shrubland	92.49
4	Degraded Land	81.75	9	Mixed Conifer Forest	105.21	14	Others	101.42
5	Broadleaf Forest	75.35	10	Grassland	98.26			

Figure 3: Predicted SOC density (1×1 km² grid) for the top 30 cm depth



The SOC stock for each grid was computed (Eq. 2) and added to estimate the overall SOC stock for the entire country. The preliminary results show that for the top 30 cm depth, Bhutan stores about 0.4 GtC with SOC density ranging from 0.45 to 315.28 tonnes ha^{-1}. As expected, the spatial distribution of SOC stock for each grid cell was also similar to the spatial distribution of SOC density with LULC, topography, and climatic regime as the main influencing factors. The SOC stock in the southern and eastern regions was relatively small as opposed to the western and northern parts of the country (Fig. 3). This is chiefly due to less forest cover and the high rate of mineralization in the eastern and southern regions, respectively. The SOC stock under different LULC types was quite similar to what Dorji et al. (2014) reported with SOC stock lowest under agricultural land and highest under forest.

Conclusions

The preliminary results show that Bhutan stores about 0.4 GtC in the top 30 cm depth. When compared to the global SOC storage (680 GtC), Bhutan stores more than 0.1% of the global SOC stock, which is almost five times more than its total land area. This clearly indicates that Bhutan has a high SOC stock but the challenge now is how to maintain it against the backdrop of increased land degradation, unsustainable land management, and climate change. Appropriate policies and sustainable management practices will have to be put in place to reduce C emission and increase C sequestration in the country.

This is the first attempt made to digitally map SOC stock in Bhutan (0–30 cm) using a small dataset. As such, the RK model predicted SOC may not be as accurate as it seems and might have a high degree of uncertainty. In this regard, more soil information, capacity building, and good access to data and statistical software will be required to come up with more accurate and reliable SOC stock estimation with less degree of uncertainty in the near future.

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Sustainable management of soil carbon and fertility in mountain area under the rapid land alteration routine based on the case study of grassland ecosystem in the Qilian mountain

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Abstract

Mountain ecosystems are among the most hostile environments humans inhabit and mountain farming is often highly specialized. Climate change and rising demand for food are rapidly altering land use, especially in the HKH region. The sustainable management of soil systems based on historical and present evaluations of land operations, soil carbon, and the role of fertilizers can support food production and ecosystem stability in the mountain. In this synthesized paper, we summarize several recommended good practices for soil fertility management in mountain areas based on the Global Environmental Fund (GEF) project conducted in the Qilian Mountains area in the northern edge of the HKH. The project made the following recommendations:

- For the alpine meadow, the cessation of tillage practice is very important for protecting soil carbon and water, as well as for preventing soil erosion.
- For the alpine steppe, the two restoration methods studied (planting grasses and abandonment of cropping) enhanced soil carbon and nitrogen levels above those of cropland but did not restore them to levels in native grasslands. The restoration of the alpine steppe by reseeding former cropland has exhibited faster recovery rates than average rates for China or globally.
- For the alpine desert, if there are no household land rights that need to be determined on alpine desert rangelands, enclosures should not be installed in such areas – neither for the protection of the landscape nor for increasing biodiversity.

Introduction

Precipitous replacement of land cover by various land use patterns has had strong impact on soil geochemical processes and ecological stability in mountain areas, especially in China, due to rapid urbanization and population growth. Qilian Mountain on the northern edge of the Tibetan Plateau is known to have remained stable under climate change and anthropogenic activities. The slopes and elevations are important for obstructing desert expansions from Inner Asia's desert, providing considerable water resources for residents as well as biodiversity in Inner Asia. The project was supported by the GEF to assess the impact of swift land alterations on the status of soil carbon and other nutrients, and to provide a basis for careful land utilization for sustainable vegetation management and ecological security.

The assessment covered major grassland vegetation types across the northern part of the Qilian Mountains, about 1,000 km from east to west in Gansu Province. The primary objective of the project was to evaluate the influence of grassland utilization and management and acquire profound knowledge of soil nutrition profile in order to identify the gaps and challenges in soil management and provide a clear roadmap for sustainable management of soil systems in China's mountain areas.

The other objective of the project was to outline the principles of rehabilitation and restoration of degraded grassland along with the effect on its soil carbon and fertilizer sequestration capacity in mountainous areas. In addition, the project aimed to evaluate the influence of different vegetation types on soil carbon and fertilizer function and management of grassland soil nutrition. Keeping this in view, we synthesized three major vegetation types (alpine meadow, alpine steppe and alpine desert) in mountain areas (Shang et al., 2012, 2014, 2017).

Study area background and methods

Study area background

The project was implemented in three regions of Gansu Province – eastern, middle and western parts of the Qilian Mountains, respectively, mainly covering four counties (Tianzhu, Sunan, Yongchang, and Subei) under the GEF project. The three rivers – Shiyang (eastern part), Heihe (middle part) and Shule (western part) – flow through the northern slope of Qilian Mountain. These rivers are the main water source of the grassland-farmland ecosystem in the northern slope of the Qilian Mountains. Based on this background and principle, we focused on the upstream grassland ecosystem in this area. The present report takes into account the change in grassland in the upstream of the three rivers and evaluates vegetation carbon function. This work would provide a scientific basis for grassland carbon management. Three types of vegetation – alpine meadow, alpine steppe and desert –were selected for this study on the northern slope of the Qilian Mountains. They are located along Qilian Mountain, from east to west.

Alpine meadows: The four study sites represented different land use types (traditional grazing, long-term cultivation activity, and abandoned cultivation) on natural meadow, which were natural meadow (NM), natural meadow cultivated about 20 years (CL20), abandoned cultivated cropland for 3 years (AL03), and abandoned cultivated cropland for 10 years (AL10). The study area was located in the headwater area of the Heihe River of Qilian Mountain, northwestern China. The study site (E 99°49′, N 38°43′) is at an altitude of 2,950 m and has a mean annual temperature of 1-3 °C.

Alpine steppe: To assess the recovery of soil carbon and nitrogen by the two restoration methods, one study area was selected which included the two methods (abandonment and reseeding) and for comparative analysis against the same background conditions (alpine steppe), cropland and native grassland. The four study sites were native alpine steppe (SL), cropland of 40-year duration (CL40), reseeded grasses (*Elymus* spp.) of 10-year duration on former oat cropland (RL10), and abandoned oat cropland of 10 years (AL10). The study site was situated in Hongwan village, Dahe township, Sunan County of Gansu Province (N: 38°57′, E: 99°30′) on the northern slope of the Qilian Mountains at the headwaters of the Heihe river. The study site has an altitude of 2,722 masl.

Alpine desert: Three study sites were selected for evaluation of the effects of prevention of grazing. The enclosure area of the study site had been fenced regularly to demonstrate the typical effects of enclosure on alpine desert rangeland. The enclosure was set up by wire fences to totally prevent grazing activity and other disturbances round the year. The distance between the three study sites was at least 100 m. Two treatments were implemented in each of the sites, one within the enclosure and the other outside it, where grazing continued as before. The study was conducted in the western part of the Qilian Mountains and Subei County of Gansu Province, at 39°36′N, 95°09′E, and altitude 2,715 masl. The area was characterized by an arid climate typical for inland China and Asia, with a desert rangeland landscape. Annual sunshine was 2,840 h, annual rainfall ranged from 86 to 220 mm and the annual average temperature was 6·3°C.

Vegetation and soil sampling

All sampling work, including soil sample and vegetation investigation, was carried out in August, which is the peak season of plant growth in the study sites. Within experimental plots (1 ha), the herbage was cut to ground level and removed from three random, widely spaced (>20 m) 50×50 cm sample quadrats. On the days that herbage samples were cut, a total of ten 3.5 cm diameter soil cores were collected on and around each of the herbage sample quadrats, to a depth >30 cm. The soil cores were divided into three sections cut at 10 cm intervals from the soil surface (i.e., 0–10-, 10–20-, and 20–30 cm layers). The ten samples collected at each quadrat site were bulked within each soil layer, so that a total of 24 composite soil samples were presented for analysis. The roots and coarse plant debris of all soil samples were discarded and sieved through a 2 mm mesh. The soil sample was used to measure pH, soil moisture, soil C (SOC), N (TN) content, and microbial biomass carbon (MBC), microbial biomass nitrogen (MBN).

Data analysis

The results of the different soil C, N quantities were analysed by two-way analysis of variance with land management and soil depth as treatment factors. Where significant treatments (different land use types) were found, individual means were compared at $P<0.05$ using a multiple range test.

Result and discussion

The alpine meadow under different land use

Table 1: **The soil characteristics of alpine meadow under four land use activity**

Soil layer and land use type		SOC (g.kg^{-1})	TN (g.kg^{-1})	MBC (mg kg^{-1})	MBN (mg kg^{-1})
0-10 cm	NM	140.1±1.0a	8.96±0.08a	1494.0±9.6a	384.8±5.7a
	CL20	62.0±1.2c	5.85±0.10d	602.6±9.5d	115.1±5.7c
	AL03	72.3±1.4b	6.10±0.07c	723.9±6.2c	151.3±3.3b
	AL10	76.3±0.3b	6.38±0.16b	771.5±8.1b	158.8±6.2b
10-20 cm	NM	75.5±0.3a	6.57±0.19a	761.2±7.5a	154.1±5.8a
	CL20	59.2±0.6c	5.18±0.08c	562.5±9.1d	91.1±8.3c
	AL03	70. 3±1.6b	5.46±0.06c	671.4±8.9c	123.3±5.2b
	AL10	75.8±1.7a	6.10±0.25b	725.2±6.6b	92.0±6.6c
20-30 cm	NM	73.6±2.6a	6.32±0.17a	709.4±9.6a	74.3±5.1a
	CL20	53.8±1.6c	4.81±0.17d	490.6±9.2d	60.6±1.5b
	AL03	66.2±0. 6b	5.26±0.12c	615.3±4.6c	76.0±3.0a
	AL10	72.3±1.3a	5.76±0.12b	679.1±8.9b	81.9±5.8a

For the alpine meadow, land use change led same variation trend of SOC, TN, MBC and MBN within soil layers and land utilization types (Table 1). The concentrations of SOC, TN, MBC, MBN were both significantly affected by land use. Here we used the SOC as an example to present the change model of soil nutrition under the land use change in the Qilian Mountains ecosystem. Both short- and long-term tillage activities have been shown to reduce soil carbon content (Kingery et al., 1996). Our results showed that long-term disturbance significantly reduced the soil carbon content in the alpine meadow in western China. Early invasion of the abandoned land by grasses leads to an increase in SOC and MBC contents of the deeper (10–20 and 20–30 cm) soil layers, equal to those in the native meadow. Land management practices affect soil microbial carbon, which mediates many processes essential for productivity and sustainability of soil (Patra et al., 2008). In rangeland areas, government policy is to stop intensive cultivation and gradually return cropland to native rangeland in mountain areas. However, completely halting cultivation within a short period would be difficult, especially in areas with dense populations and high food demand. The present study showed that after 10 years of abandonment of tillage practices, soil organic carbon content in the top 10 cm of soil was restored to 90% of that present in native alpine meadows. This equates to a mean annual rate of increase in soil organic carbon of 1.73 t C ha^{-1}, somewhat higher than the global mean rate of 0.54 t C ha^{-1} (Conant et al., 2001).

3.2 Alpine steppe under different land use

Figure 1: Soil organic carbon levels (SOC t ha^{-1}) and soil total nitrogen (TN t ha^{-1}) of the four land sites for different soil layers. The letters above the error bars indicate significant difference ($p<0.05$) among the four land use sites within each soil layer

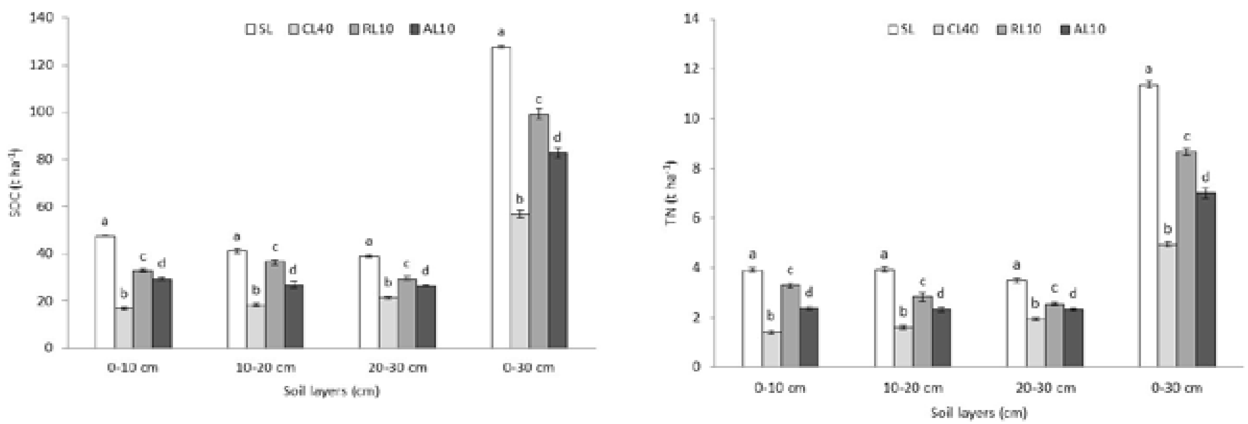
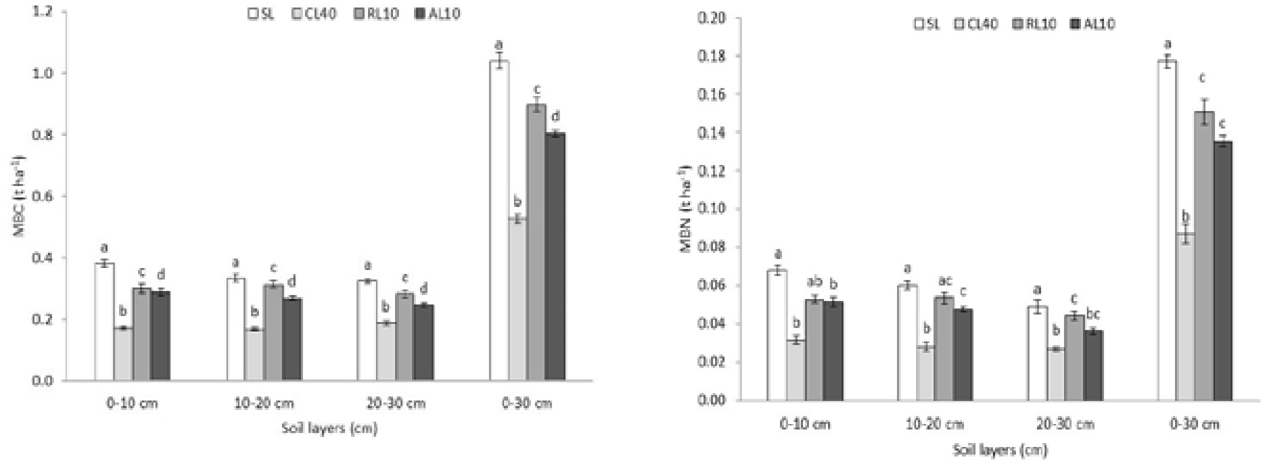


Figure 2: Soil microbial biomass carbon (MBC $t\ ha^{-1}$) and nitrogen (MBN $t\ ha^{-1}$) of the four land sites for different soil layers. The letters above the error bars indicate significant difference ($p<0.05$) among the four land use sites within each soil layer

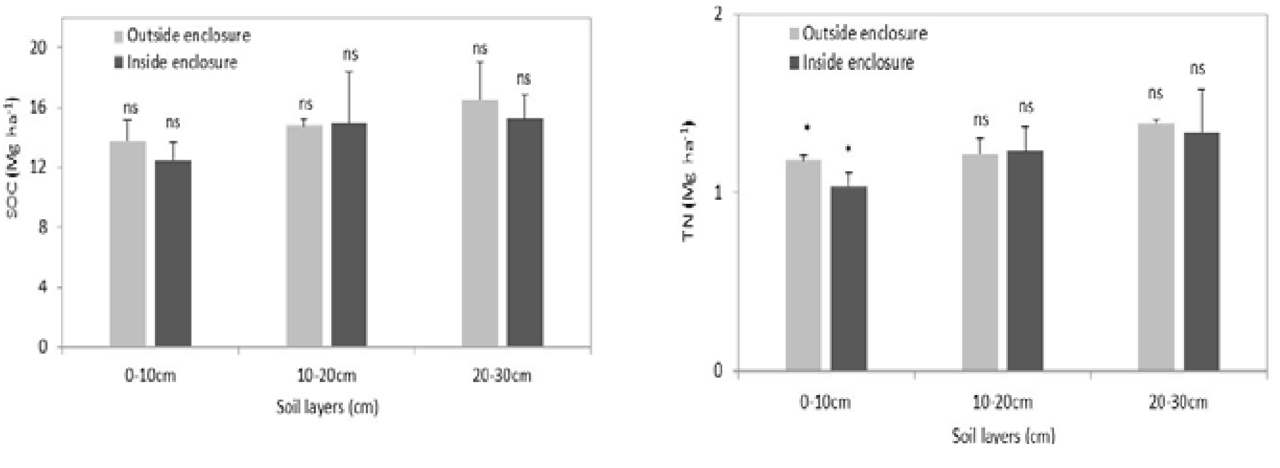


For each soil layer, the soil organic carbon (SOC) of the four sites was significantly different (p b 0.05) (Fig. 1). The natural steppe site (SL) has the most SOC storage at each soil layer and across the aggregated soil layers (0–30 cm). The variation of TN storage among the four sites in different soil layers was similar to SOC (Fig. 1). MBC storage among the four sites in each soil layer was significantly different (p b 0.05) (Fig. 2). MBC was highest for SL and lowest for CL40, the difference being significant (p b 0.05). The MBN of SL was highest among the four sites at each soil layer but was not significantly different from RL10 at 0–10 cm and 10–20 cm (Fig. 2). At 0–10 cm, there were no significant differences in MBN in CL40, SL10 and AL10. MBN of CL40 was lowest, the difference being significant at 10–20 cm and 0–30 cm. MBN were not significantly different between SL10 and AL10 at all soil layers.

Surface soil layers experienced significantly greater change than deeper layers after 40 years of cultivation in alpine steppe. Although at times mineral fertilizer was used on the cropland, mineral fertilizers have only small carbon sequestration rates, so large carbon losses from plant and microbial respiration are not prevented by cultivation (Jones et al., 2006). The restoration of alpine steppe by reseeding former cropland has a faster recovery rate than the average for China (1.304 $Mg\ C \cdot ha^{-1} \cdot yr^{-1}$) (Wang et al., 2011). Soil C and N contents are usually not restored to the same levels as the original grassland plots. According to Knops and Tilman (2000), in North America, recovery to 95% of the original soil C and N grassland levels from former cropland could perhaps take 180 years and 230 years, respectively. The current study showed the soil C and N recovery rate is higher than the average global rate (0.54 $Mg\ C \cdot ha^{-1} \cdot yr^{-1}$) in restoration of grassland from former cropland (Contant et al., 2001). Other low-cost options for quickly recovering grassland from former croplands include abandonment and enclosure of the land.

3.3 Alpine desert different land use

Figure 3: Soil organic carbon (SOC $t\ ha^{-1}$) and total nitrogen (TN $t\ ha^{-1}$) at outside enclosure and inside enclosure of alpine desert for different soil layers. The letters above the error bars indicate significant difference



($p<0.05$) among the four land use sites with each soil layer.

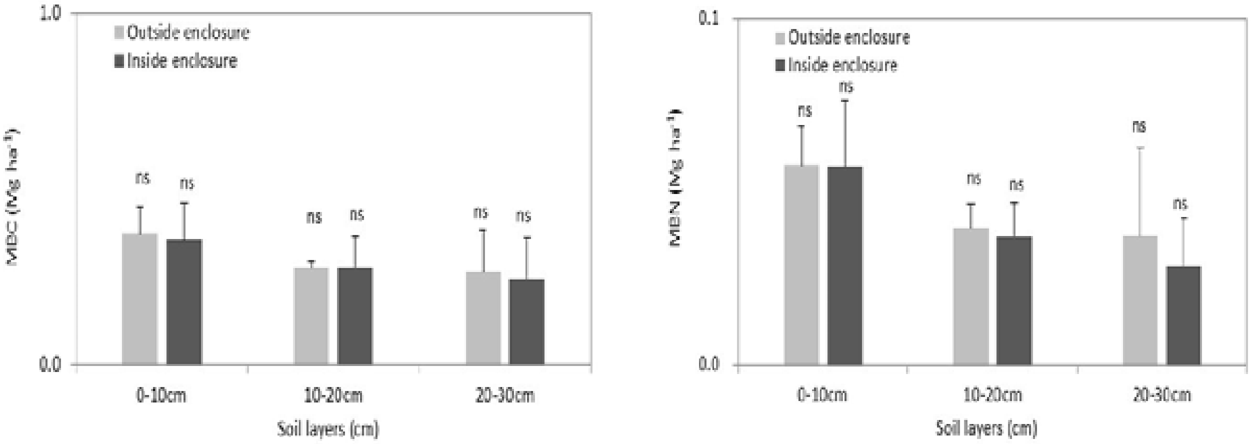


Figure 4: Soil microbial biomass carbon (MBC t ha^{-1}) and nitrogen (MBN t ha^{-1}) at outside enclosure and inside enclosure of alpine desert for different soil layers. The letters above the error bars indicate significant difference ($p<0.05$) among the four land use sites with each soil layer

It was found that the SOC storage was higher in open rangeland than after six years of enclosure in first soil (0–10 cm) and third soil (20–30 cm) layers (Fig. 3). The TN in all soil layers was higher outside the enclosures than inside after six years of enclosure. No significant differences in soil C and N contents were found in any of the study sites following six years of enclosure, except that the TN content in the 0–10 cm soil layer was significantly ($p<0{\cdot}05$) higher outside than inside the enclosures (Fig. 3). Generally, the MBC content inside the enclosures was lower than that outside except in the second soil layer (10–20 cm) (Fig. 4). The MBN contents outside the enclosures were higher than that inside in all soil layers (Fig. 4).

The present study found that six years of grazing prevention by enclosure did not improve soil C and N storage in the alpine desert rangeland; moreover, in most cases, a negative but insignificant effect was found. Compared to enclosures at high altitudes (2,700 m), as in this study, enclosures in low-altitude (1,400 m) alpine desert rangelands showed significant long-term effects of increasing soil C and N accumulation (Zhou et al., 2011). In desert areas of northern China, soil C and N losses were found to result from disturbance, mainly caused by wind erosion, and the layer most sensitive to these effects was the upper soil layer (<10 cm) (Su et al., 2004). Under low rainfall conditions, altitude has a significant influence on these results. SOC storage in the various soil layers in the alpine area responded differently to long-term enclosure. Alpine desert rangelands have poor forage productivity for grazing and breeding livestock and low stocking rates because of the very harsh environment. These areas are better left as natural landscapes for the preservation of wild animals and biodiversity.

4. Conclusion and applications for soil fertilization of mountain areas

In the alpine meadow, change in land use affects soil characteristics, and cultivation can reduce soil organic carbon storage. The government policy over the past decade has been to encourage farmers to abandon intensive cultivation and allow rangelands to revert to native pasture. However, in some areas, total abandonment of all cultivation practices is impractical due to food crop requirements of the local population. Nevertheless, the cessation of tillage practices is very important for the protection of soil carbon and water, as well as for the prevention of soil erosion.

For the alpine steppe, long-term cultivation led to reduced storage levels of soil carbon and nitrogen. The two restoration methods studied (planting grasses and abandonment of cropping) enhanced soil carbon and nitrogen levels above those of cropland but did not restore them to the levels of native grasslands. The restoration of alpine steppe through reseeding of former cropland displayed faster recovery rates than average rates for China or globally. Thus, the two restoration methods could be recommended for returning cultivated land back to grassland.

For the alpine desert, although previous studies have shown benefits of building enclosures in desert rangelands in China, the current study has not confirmed these findings. Six years of enclosure to prevent grazing has not significantly improved soil C and N storage capacity of the alpine desert soil, although the vegetation biomass and cover increased. The suggestion was that if there are no household land rights that need to be determined on alpine desert rangelands, enclosures should not be installed in such areas, neither for protection of the landscape nor for increasing biodiversity.

Acknowledgement

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Soil dynamics under snow cover and climate change

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Abstract

The snow cover extent in the Northern Hemisphere has been decreasing since 1960 due to global climate warming, and the process is likely to continue. Reduced seasonal snow cover inhibits available soil water and slows down soil organic matter decomposition and nitrogen mineralization, because colder soil temperature leads to decreased microbial biomass, activity and alteration of community structure. Plants may receive less nutrients after snowmelt, which can further disrupt plant population interactions due to difference in temperature sensitivity, leading to mismatched phenology and/or dispersal patterns. Moreover, the effects of reduced snow cover on soil fauna in the future remain unknown. In the context of global social and environmental changes, it is important to manage soil fertilizer according to the dynamics of soil nutrients in the area covered by seasonal snow.

Changes in seasonal snow cover characteristics in the context of global climate change (IPCC, Climate Change 2014 Synthesis Report)

Changes in seasonal snow cover characteristics in past and their causes in Northern Hemisphere

Evidences of changes in Northern Hemispheric snow cover have been found in recent years. For example, the rate of ice mass loss from the Greenland ice sheet has very likely increased over the period 1992 to 2011. Also, the Arctic sea ice extent has very likely decreased at a rate of 3.5% to 4.1% per decade. Overall, there is very high confidence that the extent of the Northern Hemisphere snow cover has decreased since the mid-20th century by 1.6% [0.8 to 2.4%] per decade for March and April, and 11.7% per decade for June, over the period 1967 to 2012.

Global climate warming seems to be the main cause of snow cover change. According to thermophysics of ice, climate warming might increase ice melt and reduce ice recruitment. And it is extremely likely that most of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forces. Anthropogenic influences have likely affected the global water cycle since 1960 and contributed to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. Furthermore, anthropogenic influences have very likely contributed to the Arctic sea-ice loss since 1979.

The future trend of changes seasonal snow cover characteristics in Northern Hemisphere

In order to control anthropogenic GHG emissions, the Representative Concentration Pathways (RCPs) was published. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5).

Although a simulating model shows the projected future trend of the Northern Hemisphere seasonal snow cover extent obviously depends very much on the RCP scenario, the reduced Northern Hemisphere seasonal snow extent clearly continues in all RCP scenarios. Compared with the period of 1986-2005, the average Northern Hemisphere-influenced seasonal snow cover extent varies from 7.2% for RCP2.6 to 24.7% for RCP8.5 at the end of the 21st century (2080-2099) (Table 1). The trend also indicated that the reduction of snow cover and shortening of the snow season through earlier melt is strongest in the low-latitude area, since climate warming immediately translates into a replacement of solid by liquid precipitation (Brutel-Vuilmet et al., 2012).

Effects of snow cover on soil physico- and bio- chemical properties on the alpine ecosystems

Effects of snow cover on soil physicochemical properties on the alpine ecosystems

Snow cover might influence many aspects of soil physicochemical properties. The characteristics of seasonal snow cover such as depth, length and period can affect soil temperatures during the non-growing season. We found

Table 1: **Northern Hemisphere ice-free land (NH-ifl) seasonal snow cover change (in %, $\pm \sigma$ inter-model spread) relative to 1986-2005, for the four RCPs (March-April average). The number of models taken in account in each scenario is given in parentheses after the scenario name**

Scenario	RCP2.6 (15)	RCP4.5 (22)	RCP6.0 (12)	RCP8.5 (19)
2016-2035	-5.6±2.3	-5.4±2.0	-4.6±1.6	-6.1±2.4
2080-2099	-7.2±3.8	-12.9±4.2	-15.2±5.8	-24.7±7.4

IPCC (2014)

that shallow (<20 cm) snowpack leads to more freeze-thaw cycles and greater soil temperature fluctuation, while late development of insulating snowpack (> 30 cm) results in lower soil freezing temperature and less temperature fluctuation in alpine meadows of the Tibetan Plateau (Liu et al., 2010). Moreover, it is well known that seasonal snow cover usually inhibits available soil water and infiltration. Evidence suggests that removed snow cover significantly reduces soil volumetric water content and leaching during spring (Hardy et al., 2001). In addition, an experiment conducted in a North American forest found that after removal of snow cover, the organic matter concentration of both soil micro- and macroaggregate fractions increased (Steinweg et al., 2008).

As for carbon and nitrogen nutrients, net N and N/C mineralization potential of macroaggregate fractions increased while no changes in C mineralization were detected in the above-mentioned experiment. The mechanism might be that soil freezing could break down larger litter particles that provide more soil N nutrient (Steinweg et al., 2008). Additionally, a study in the eastern Tibetan Plateau found that deeper snow cover reduced soil NH_4^+-N content while it did not change net N mineralization (Hu et al., 2014). In contrast, it was found that deeper snow cover increased over-winter N mineralization and thereby altered the amount and timing of plant-available N in the alpine meadow and the Arctic tundra ecosystems (Liu et al., 2011; Schimel et al., 2004). This suggests that in spite of snow cover, other factors such as climate, microbial type, agrotype and ecosystem type could also contribute to soil N nutrient variabilities.

Effects of snow cover on soil biochemical properties on the alpine ecosystems

Normally, microbial activity in alpine cold season is low but cumulatively significant. Warmer soil temperature due to deeper snow may increase microbial activity and organic matter decomposition, thus improving nutrients available to plants in the following growing season. For instance, it was found that deeper snow may increase microbial nutrient pools in Canada low Arctic tundra (Buckeridge & Grogan, 2008).

Even at extreme high-altitude sites (3700m), snow cover can remain around 0℃ under its pack for months, which allows the proliferation of a large and diverse cold-adapted microbial community (Ley et al., 2004). A study indicated that in the whole period of snow cover, under-snow soil microbial biomass N increased very slowly till snowmelt when the microbial biomass N started to decrease (Brooks et al., 1998).

The effects of snow cover on microbial community structure remain poorly understood. In the Arctic tundra, microbial biomass at different snow depths may be consistently dominated by fungi (Buckeridge & Grogan, 2008). This is probably because bacterial lysis may be more stable under freeze-thaw conditions and fungi under temperature fluctuations (Sharma, et al., 2006). Furthermore, genomic sequences indicated fungi constituted the largest part of microbial sequence reads on the surface of 45cm-thickness snowpack during Arctic spring snowcover (Maccario et al., 2014).

Predicting the changes in soil properties in the context of seasonal snow cover change

Snow cover extent and duration may decrease along with global warming as the simulating model shows (Brutel-Vuilmet et al., 2012). Soil temperature may decrease, allowing more frost to form and less water to leach (Hardy et al., 2001).

The results of Steinweg's 2008 study showed that less snow cover may allow faster breakdown of large litter particles, thus increasing organic matter and N mineralization in soil. Furthermore, decreased snow cover may advance the timing of soil freezing-thawing, which may contribute to microbial nutrient release, thus enhancing nutrient leaching in early spring before plants are active (Tan et al., 2014).

In colder temperatures due to less snow cover, microbial activity and organic matter decomposition may decrease and less nutrients may be provided to plants after snowmelt (Buckeridge & Grogan, 2008). Under the condition of deep snow cover, the alpine/tundra microbial communities take fungi as the representative. When snow cover decreases, Bacteroidetes/Chlorobi are replaced by fungi and become the largest microbial community (Maccario et al., 2014). In general, considering other factors such as soil condition, ecosystem type and microbial type, it is necessary to explore the corresponding changes in soil dynamics in the context of changes in snow cover in the different ecosystems.

Effects of changes in soil dynamic on ecosystem services in areas with seasonal snow cover

Regional vegetation patterns in alpine, Arctic and cool temperate landscapes strongly depend on the distribution and physical characteristics of the snowpack (Walker et al., 1993). These represent snow cover characteristics such as distribution, longevity, depth, density, and hardness, which determine the populations' ability to survive in snow-covered regions. Under global warming conditions, plant population interactions may be disrupted by differences in temperature sensitivity, leading to mismatched phenology and/or dispersal patterns (Berg et al., 2010). Liu et al. have proved that earlier flowering and longer flowering duration for perennial graminoids (P. pratensis, K. setchwanensis, respectively) and earlier and shorter duration of fruiting for the annual forb G. paludosa resulted from redistribution of dormant season and spring precipitation (i.e., snowfall) to summer (i.e., rainfall) in the alpine meadow of the eastern Tibetan Plateau.

According to Maccario's research, less snow cover may lead to alteration of microbial community structure that takes the Bacteroidetes/ Chlorobi group as the representative; thus soil fauna may be influenced because numerous soil nematodes prey on these microbes. Moreover, in some cases subnival animal activity will also influence nutrient availability. For example, lemmings can reduce the standing crops of vegetation (live and dead aboveground biomass) by 50% of the annual aboveground production and 20% of the total annual production and redistribute nutrients through the excretion of faeces and urine (Walker et al., 1999). Therefore, it could have a far-reaching effect on the material cycle and energy flow in the ecosystems with seasonal snow cover, such as alpine ecosystems. Estimates of species loss due to climate warming seem uncertain (Thuiller et al., 2004), and this can partly be attributed to inaccurate predictions of the rate and extent of global climate change. Regardless of the degree or nature of climate change, the structure and functioning of alpine ecosystems are bound to be deeply affected and ecosystem services will also be transformed in future.

Suggestions

- Strengthen the monitoring to dynamics on seasonal snow cover and soil nutrients, especially during the phases of snow melt in spring.
- Flexible and scientific management to apply fertilizer in the alpine on the basis of definite soil fertility.
- Consider the application to targeted microbial manure

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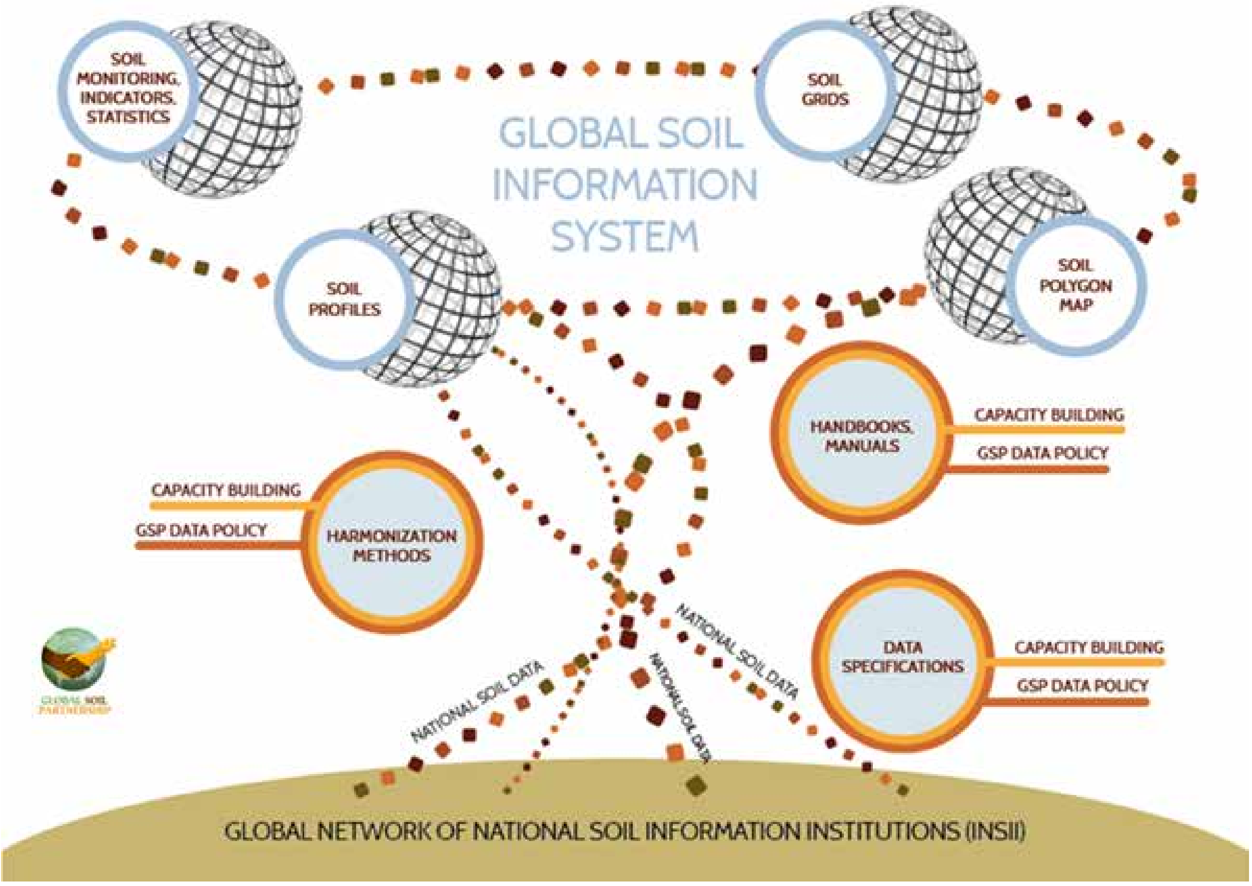
Theme: Soil information system

Soil information has become increasingly important to maintain disciplines for the implementation and monitoring of various efforts on land resource management.



Source: Website of ISRIC—World Soil Information

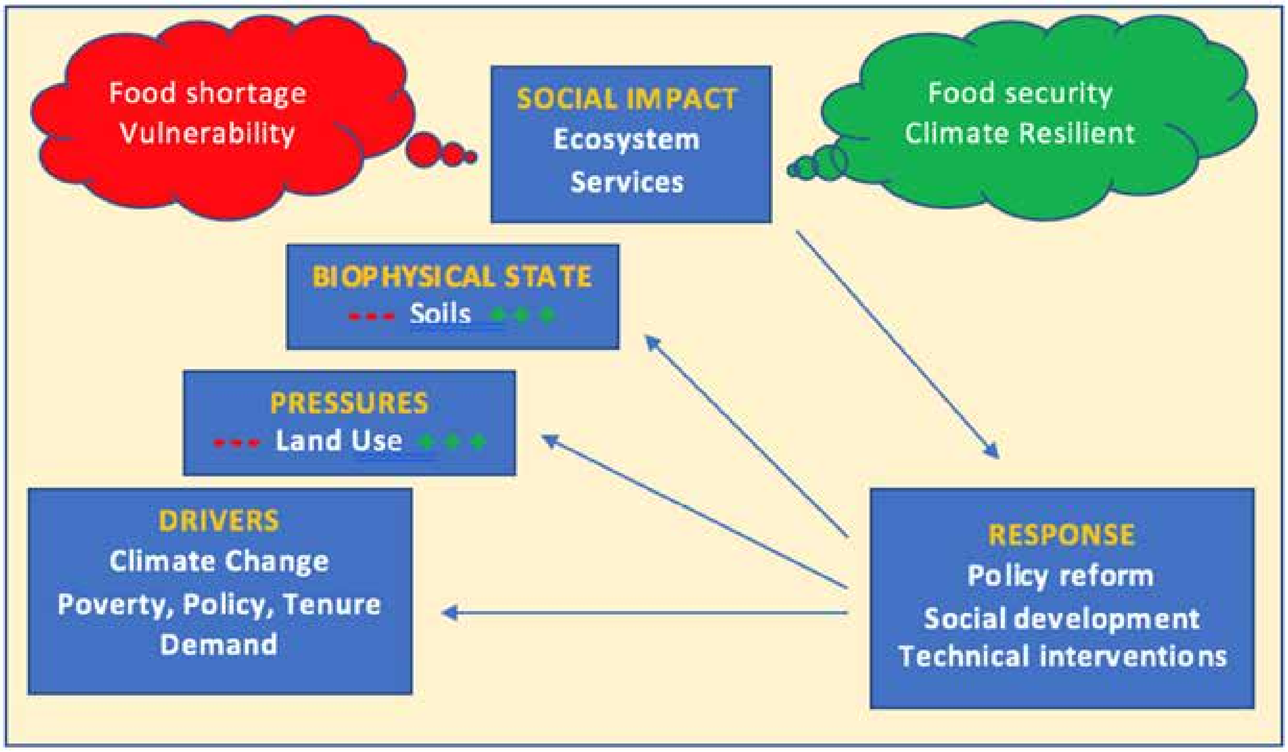
A soil information perspective on food security, climate change and sustainable management of land and water

Jan de Leeuw and Rik van den Bosch, ISRIC – World Soil Information, Wageningen, The Netherlands

Soils are an important component of the natural capital on which people depend. They provide the resources that allow plants to photosynthesize and produce food, fibres and other biological commodities. Soils also provide us with ecosystem services such as the regulation of water flows and the mitigation of climate change through sequestration of carbon and the significant stocks of organic carbon that are stored in soils.

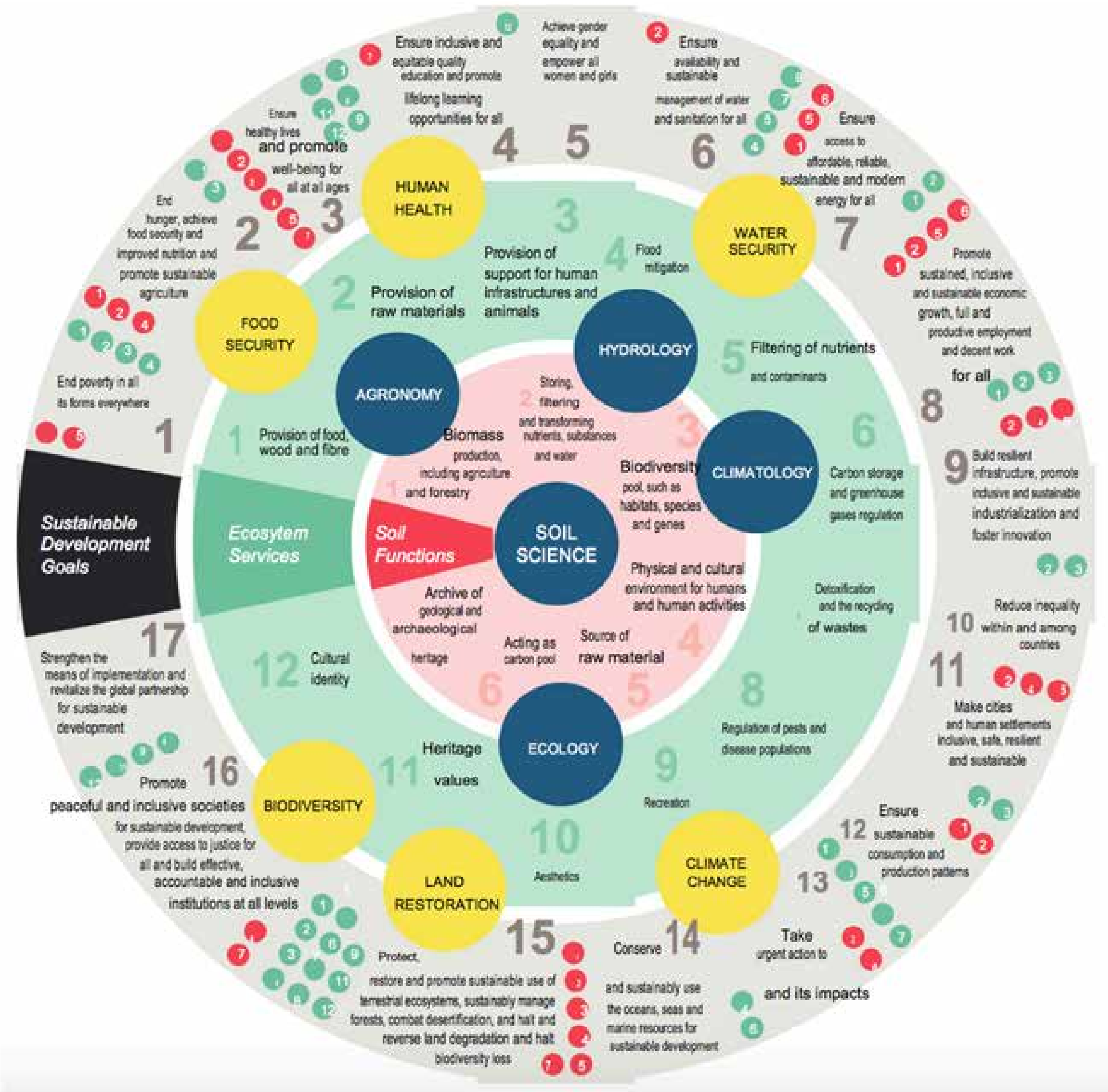
Yet, despite the many services that they provide, soils are under pressure in many parts of the world, because of unsustainable land use (Figure 1) that is resulting from drivers of change such as climate change, inadequate policies, poverty, land tenure and growing demand for food and other commodities. This may result in soil degradation, which is defined by FAO (undated) as "a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries". Soil degradation results in social impacts in that they do not provide the normal goods and services of the particular soil in its ecosystem.

Figure 1: DPSIR (Drivers, Pressure, State, Impact and Response) model of the effects of various drivers of change and unsustainable land use on the health of soils and their ability to provide ecosystem services and benefits to people



The ability of soils to provide these ecosystem services is gradually declining for a number of reasons. Lands with productive soils are being lost – for example, to urbanization and the development of infrastructure. Soils are also undergoing degradation in many parts of the world. This loss of productive potential is worrying given that humanity has to deal with climate change and that 11 billion people have to be fed at the end of the 21st century. To address this undesirable loss of productive soils, the UNCCD has developed the goal of achieving Land Degradation Neutrality (LDN) by 2030 as the Sustainable Development Goal SDG 15.3. However, SDG 15.3 is not the only development goal benefitting from the services provided by soils. Soils contribute significantly to many other sustainable development goals (Figure 2; Keesstra et al., 2016) including food security (SDG2), human health (SDG 3), water security (SDG 7), climate change (SDG 14), and biodiversity (SDG 16).

Figure 2: Scheme of the role of soils and soil science to ecosystem services and the Sustainable Development Goals (Source Keesstra et al. 2016, CC BY 3.0)

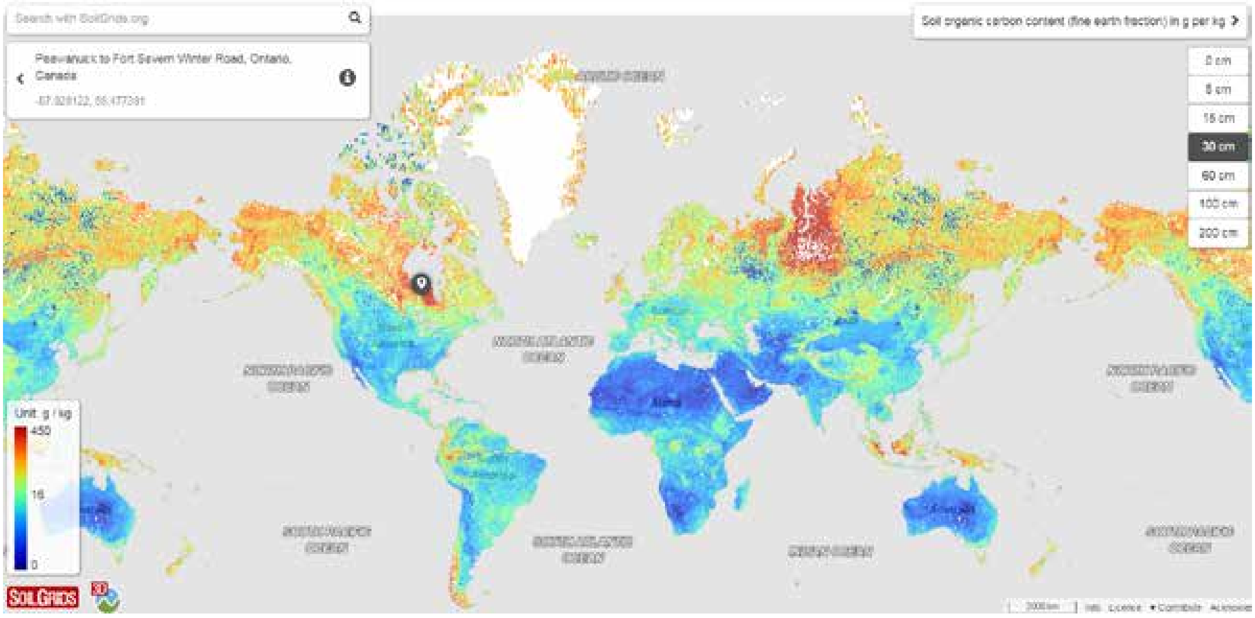


Proper soil management is needed to achieve these various Sustainable Development Goals. Availability of information on the status of soils is important for guiding policies and decisions on managing soil health and protecting and restoring degraded soils and thus to achieve the various Sustainable Development Goals.

For example, information on soil organic carbon (SOC), one of the sub-indicators for SDG 15.3, is being used to support the LDN agenda in various ways. SOC information is being used in the setting of LDN targets at the national level. It will also be used as an indicator to monitor the impact of interventions of projects that aim to contribute to the LDN agenda. Finally, information on SOC will also be used by signatories of the UNCCD to report their progress towards achieving the LDN targets.

There is a variety of initiatives to support the UNCCD with SOC information. First, the UNCCD developed a Good Practice Guidance for the SDG 15.3 indicator (UNCCD, 2017). Second, the Global Soil Partnership (GSP), through a consultative process with national parties, developed a Global Soil Organic Carbon map (GSOC Map) to support the Sustainable Development Goal Indicator 15.3.1 (FAO, 2017). Third, while waiting for the result of this country consultative process, ISRIC-World Soil Information supplied the UNCCD with national-level information on soil organic carbon using SoilGrids (Hengl et al., 2016) as a baseline for SDG 15.3 (Figure 3).

Figure 3: Soil Organic Carbon content (g per kg) at 30 cm depth according to SoilGrids, a web portal for Global Soil Information (Hengl et al. 2016).



Notwithstanding the above initiatives, significant challenges remain. The implementation of the LDN agenda requires regular updating of information on SOC. This requires first of all an intensification of in-situ SOC measurements. Ideally, to allow inter-comparability of the information reported, such in-situ measurements would be carried out according to harmonized procedures. Various initiatives are under way to develop guidelines for the reporting of the status of SOC and the associated in-situ measurement and reporting of SOC. Various groups are working on developing space time modelling approaches to predict the changes in soil organic carbon from changes in land use detected by remote sensing and other more easily observed environmental variables.

The above illustrates the importance of soil information for Sustainable Development Goals in general and the land degradation neutrality goal in particular. It is clear that the SDGs have created a demand for soil information. This is an opportunity for the soil science community. At the same time, they have created a challenge, because soil information requires in-situ measurements, which are labour-intensive and costly. These challenges are easier to address through partnerships that bring together soil scientists from across the globe and the region to share experiences, support each other in uptake of technical innovation in soil sampling and analysis and harmonize methods.

During this workshop, ICIMOD brought together the soil science community working in the Hindu Kush Himalaya region. This community expressed an interest in developing a joint agenda to strengthen the application of soil science to improve soil conservation in the region. We recommend that ICIMOD consider taking the lead role in developing regional partnerships to mobilize this dispersed community, to share experiences, develop joint projects and enable the members of this community to use their expertise in addressing the issue of soil conservation in the Hindu Kush Himalayan region. ICIMOD may establish a south-south learning platform to 1) conduct soil related research at the regional scale, 2) share best practices for replication and upscaling, and 3) coordinate joint meetings on mountain soils.

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