FOREST ECOSYSTEM SERVICES GOVERNANCE, SUPPLY AND DEMAND IN TAJIKISTAN

Dissertation

to attain the academic degree of Doctor of Natural Science (Dr. rer. nat.)
of the Bayreuth Graduate School of Mathematical and Natural Sciences
(BayNAT)

University of Bayreuth

Bunafsha Mislimshoeva

MSc

Born November 23, 1985

UNIVERSITÄT BAYREUTH

Bayreuth, April, 2016

This doctoral thesis was prepared at the Professorship of Ecological Services, University of Bayreuth, between November 2011 and December 2015. It was supervised by Prof. Thomas Koellner, Prof. Cyrus Samimi and Prof. Carl Beierkuhnlein.

This is a full reprint of the dissertation submitted to obtain the academic degree of Doctor of Natural Sciences (Dr. rer. nat.) and approved by the Bayreuth Graduate School of Mathematical and Natural Sciences (BayNAT) of the University of Bayreuth.

Date of submission: 21.12.2015

Approval by the steering committee: 15.01.2016

Date of scientific colloquium: 05.04.2016

Acting dean: Prof Stephan Kümmel

Doctoral committee:

Prof. Thomas Koellner (Erstgutachter)

Prof. Heike Feldhaar (Zweitgutachter)

Prof. Bernd Huwe

Prof. Eberhard Rothfuß (Vorsitz)

Acknowledgment

I would like to convey my deepest gratitude to many people who supported me through the ups and downs of this long journey.

Foremost I would like to thank my supervisor Prof. Thomas Koellner for his guidance and for all what he have taught me during these years. Furthermore, I thank Prof. Cyrus Samimi and Prof. Carl Beierkuhnlein for their valuable support to this work.

My sincere gratitude goes to the people and colleagues in the research areas – Dushanbe, Khorog and Ishkashim district. Without them, this work would not exist. I am also very thankful to all those who provided their direct and indirect support during the field work.

I owe a lot of thanks to all co-authors Abdulnazar Abdulnazarov, Cyrus Samimi, Manuchehr Fezakov, Paul Schumacher, Peter Herbst, Robert Hable and Thomas Koellner for their time and knowledge they have shared. Alongside I would like to thank André Fabian for his valuable feedback and several excellent anonymous Reviewers and Editors, who improved the quality of the published manuscripts enormously.

I am highly indebted to Martin for having the endless patience and motivation to go through the drafts of this thesis again and again. Many thanks also go to Anna, Raphael, Paul and Zaynura.

The successful completion of this thesis would have not been possible without the joint financial support of the University of Central Asia and the German Academic Exchange Service. Besides this, I am very thankful to the University of Bayreuth for always being there for its students when needed.

Among friends it is difficult for me to name some. Those who were, are and will be part of my life do not need to be listed here. They know it.

Without the emotional support of my family I would not have been there, where I am today. There is nothing more to say.

Last but not least, what is often forgotten in the acknowledgments in this field of research is nature… the forests which provide life...

Table of content

Summary

In the last few decades the worldwide population growth and consequently the increasing demand for resources have put enormous pressure on the environment. To such an extent that in technically advanced countries some services of nature are replaced or expanded by anthropogenic inventions. For many services the spatial dimension of supply and demand go beyond a single region, thereby creating increased globalized environmental impacts. In other parts of the world, especially rural areas of developing countries, the flow of ecosystem goods and services remains local, thus also increasing local environmental impacts. This is especially the case in arid high mountainous areas, where isolation, scarce resources, and harsh climatic conditions additionally make people's livelihood more challenging. Here, the demand for energy, mainly for heating and cooking, is significantly high. However, the local heterogeneity of energy usage, flow and management remains largely unknown (chapter 3).

Against the global and regional backgrounds, this thesis aims at understanding the local energy consumption patterns. Additionally, it focuses on households' firewood consumption and evaluating the factors influencing it. Furthermore, forest firewood supply, demand and governance at the local and national scales were analyzed in the context of developing countries as well as countries in transition. Tajikistan was selected as a research area, due to its unique, but at the same time "representative" history of energy use. The local population currently needs to cope with the energy situation, and so understanding the heterogeneity of energy use in the arid high mountainous areas of the country is of special interest (chapter 5). Here, many factors (biophysical, socio-economic, governance) can potentially influence the amount of energy used. This was analyzed in the first research paper of this thesis, where data was collected through household interviews. The paper concluded that animal dung and firewood count as the main sources of energy in the rural mountainous areas of Tajikistan. The amount of consumed firewood was positively influenced by elevation, size of a household's private garden and total hours of heating, while education level and access to a reliable supply of electricity influenced firewood consumption negatively. The results of the paper also showed that the main sources of firewood are private gardens, forests, gorges, along the roads and agricultural fields (chapter 6.1). While quantification of firewood sources outside of forests remains a challenge for a number of reasons, in the second paper forest firewood supply and demand was analyzed. The results suggest that in most case study areas the budget between forest firewood supply and demand remain positive, but are subject to

uncertainties and must be interpreted with caution (chapter 6.2 and 9). Closely related to the second paper, in the third, forest biomass was estimated for the research area with high-resolution RapidEye satellite data. This paper showed that in the semi-arid to arid regions red edge and texture attributes improve the model results for woody biomass estimation (chapter 6.3 and 10). The opportunities to integrate the results of this study in spatial analysis with forest firewood demand are highlighted in the research outlook (chapter 13).

Management of not only firewood, but overall forest governance is an important aspect of sustainable use of these resources. The fourth paper captured a broader context of current pathways of forest governance in Tajikistan and the enhancement of forest ecosystem services (ES). In-depth interviews were conducted with experts at national level. The results indicated that establishment of new institutional networks leads the sector towards good forest governance. However, challenges in creating sound legal frameworks, decision-making transparency and implementation enforcement remain to be overcome (chapter 6.4 and 11).

Though several uncertainties and limitations are attached to this thesis (chapter 12 and 13), it nevertheless contributes new empirical insights to advance understanding of: i) the energy situation, ii) the role of ES to meet the energy demand, iii) the situation of supply and demand and iv) governance of ES. The results are not only of significance for the high mountainous areas of Tajikistan, but also regions with similar history, socio-economic and climatic conditions, such as former Soviet countries. Further research priorities should be set to further qualitative and quantitative empirical and ecological data collection in order to improve understanding of the changes in the availability and usage of ES in people's livelihood. The changes are likely to become extremer, given a broader context of climate change in vulnerable mountainous areas of Central Asia. In this context, many issues remain critical for research and can help lead to decreasing the pressure on the scarce natural resources of the region (chapter 13). These include the impact of climate change on land use; the provision of multiple ES; adaptation strategies for occurrences of deficient ES; spatial and temporal ES flows and their synergies and trade-offs; alternative strategies for increasing ES supply and decreasing demand.

Введение

Рост населения, наблюдаемый в последние несколько десятилетий во всем мире и, вызванное им увеличение спроса на ресурсы оказывают огромное давление на окружающую среду. В технически развитых странах некоторые природные услуги были заменены или усовершенствованы с помощью изобретений человека, когда другие услуги выходят за рамки одного региона, создавая интенсивное глобализованное воздействие на окружающую среду. В других частях мира, особенно в сельских районах развивающихся стран, поток экосистемных услуг остается локальным, таким образом увеличивая воздействие на окружающую среду на местном уровне. Особенно это касается засушливых высокогорных районов из-за их изолированности и дефицита ресурсов, где суровые климатические условия усложняют жизнь населения. Здесь спрос на энергию, главным образом для отопления и приготовления пищи, очень высок. Тем не менее, неоднородный характер использования энергии, ее поток и управление на местном уровне остаются в значительной степени неизученными (глава 3).

На глобальном и региональном фоне данная диссертация направлена на понимание местных моделей потребления энергии. Кроме того, она нацелена на изучение потребления дров домохозяйствами и оценку факторов, влияющих на него. Предложение и спрос на дрова, а также управление на местном и национальном уровнях были проанализированы в контексте развивающихся стран и стран с переходной экономикой.
В качестве изучаемого региона был выбран Таджикистан в связи с его уникальной, но в то же время «репрезентативной» историей использования энергии. Местное население в настоящее время испытывает трудности, связанные с энергетической ситуацией, и поэтому понимание неоднородности использования энергии в засушливых высокогорных районах страны представляет особый интерес (глава 5). В данной стране существует много факторов (биофизических, социально-экономических, управленческих), которые могут потенциально влиять на количество используемой энергии. Это было проанализировано в первой исследовательской работе данной диссертации, для которой данные были собраны путем проведения опроса в домохозяйствах. Результаты показывают, что навоз и дрова считаются основными источниками энергии в сельских горных районах Таджикистана. На количество потребляемых дров положительно повлияли высота расположения, размер частного сада домохозяйства и общее количество часов отопления, в то время как уровень образования и доступ к надежному снабжению электроэнергии повлияло на потребление дров отрицательно. Результаты

также показали, что основными источниками дров являются частные сады, леса, ущелья, местности вдоль дорог и сельскохозяйственных угодий (глава 6.1). В то время как количественная оценка источников дров за пределами лесов остается проблемой по ряду причин, во второй работе было проанализировано предложение и спрос на дрова. Результаты показывают, что в большинстве изучаемых районов баланс между поставками дров из леса и спросом остается положительным, но связан с неопределенностью и должен интерпретироваться с осторожностью (глава 6.2 и 9). Тесно связанная со второй работой и представленная в третьей, лесная биомасса изучаемого района оценивалась с помощью спутниковых данных высокого разрешения RapidEye. Эта работа показала, что в полузасушливых и засушливых регионах красные края и текстурные параметры улучшают результаты модела для оценки древесной биомассы (глава 6.3 и 10). Возможности для интеграции результатов этого исследования в пространственный анализ со спросом дров выделены в перспективе исследования (глава 13).

Управление не только дровами, но в целом управление лесами является важным аспектом устойчивого использования этих ресурсов. Четвертая работа охватывает более широкий контекст текущего управления лесами в Таджикистане и улучшения лесных экосистемных услуг (ЭУ). Были проведены глубинные интервью с экспертами на национальном уровне. Результаты показали, что создание новых институциональных сетей приводит эффективному управлению лесами. Тем не менее, еще предстоит преодолеть проблемы, связанные с созданием эффективной законодательной базы, прозрачностью принятия решений и обеспечением реализации (глава 6.4 и 11).

Несмотря на то, что с данной диссертацией сопряжена некоторая неопределенность, а также ограничения (глава 12 и 13), она, тем не менее, предоставляет новые эмпирические знания для углубленного понимания: а) энергетической ситуации, б) роли ЭУ в удовлетворении спроса на энергию, в) ситуации в области спроса и предложения и г) управления ЭУ. Результаты важны не только для высокогорных районов Таджикистана, но и регионов с похожей историей, социально-экономическими и климатическими условиями, такими как страны бывшего Советского Союза.

Необходимо определить дальнейшие приоритеты научных исследований для последующего сбора качественной и количественной эмпирической и экологической информации, которая поможет улучшить понимание возможных изменений и использование ЭУ в жизни людей. Изменения могут стать более экстремальными, учитывая более широкий контекст изменения климата в уязвимых горных районах Центральной

Азии. В этом контексте многие вопросы очень важны для исследования и их понимание может помочь снизить давление на скудные природные ресурсы региона (глава 13). Они включают в себя влияние изменения климата на землепользование, стратегии адаптации для дефицитных ЭУ, пространственные и временные потоки ЭУ и их синергизм, а также альтернативные стратегии для увеличения предложения и снижения спроса на ЭУ.

Zusammenfassung

Der Druck auf natürliche Ressourcen ist in den letzten Jahrzehnten durch das weltweite Bevölkerungswachstum und dem daraus resultierenden Bedarfsanstieg enorm gestiegen. Das geht soweit, dass in weiter entwickelten Ländern Dienstleistungen der Natur schon durch anthropogene Eingriffe ersetzt oder erweitert werden müssen. Die räumliche Dimension der Nutzung und Bereitstellung von natürlichen Dienstleistungen geht in vielen Fällen über einzelne Region weithinaus, dementsprechend haben Umweltauswirkungen einen globalen Charakter. In anderen Teilen der Welt, vor allem in den ländlichen Gebieten von Entwicklungsländern, ist der Fluss von Ökosystemdienstleistungen rein auf die lokale Ebene begrenzt. Hier steigen dann dementsprechend lokal die Umweltauswirkungen enorm an. Dies trifft besonders auf isolierte, aride Hochgebirgsregionen zu, wo klimatisch bedingt knappe Ressourcen und extreme Umweltbedingungen das Leben der Bevölkerung erschweren. Der Energiebedarf, besonders für Heizen und Kochen, ist signifikant hoch. Jedoch, ist bisher wenig über die Heterogenität der Energienutzung und deren Management sowie räumliche Dimension bekannt (Kapitel 3).

Vor diesem globalen und regionalen Hintergrund, zielt diese Dissertation darauf ab ein besseres Verständnis über das lokale Energienutzungsmuster zu erlangen. Zusätzlich legt sie ihren Fokus auf den Verbrauch von Feuerholz auf Haushaltsebene und welche Faktoren diese beeinflussen. Des Weiteren wurden der Bedarf, die Verfügbarkeit und das Wirtschaften von Feuerholz auf der lokalen und nationalen Ebene analysiert und im übergreifenden Kontext von Entwicklungs – und Transformationsländer. Tadschikistan wurde auf Grund seiner einzigartigen und „repräsentativen" Geschichte zur Energienutzung als Forschungsregion ausgewählt. Da die lokale Bevölkerung mit dem Ernst der Lage in der Energiesituation umgehen muss, ist ein besseres Verständnis der Energienutzung in der ariden Hochgebirgsregion des Landes von sehr großer Bedeutung (Kapitel 5). Hierbei können mehrere Faktoren (biophysikalische, sozio-ökonomische, steuerungstechnische) potenziell den Bedarf an Energie beeinflussen. Dies wurde im speziellen im ersten Artikel untersucht. Dafür wurden Daten mit Hilfe von Interviews auf Haushaltsebene gesammelt. Der Artikel zog den Schluss, dass Viehdung und Feuerholz als Hauptenergiequellen in den ländlichen Regionen von Tadschikistan gelten. Die Menge genutzten Feuerholzes korrelierte positiv mit der Höhe, Gartengröße eines Haushalts, und Gesamtstunden fürs Heizen. Wobei Bildungsniveau, und Zugang zu verlässlicher Elektrizitätsversorgung Feuerholznutzung negativ beeinflusste. Weitere Ergebnisse zeigten, dass Hauptbezugsquellen für

Feuerholz Gärten, Waldflächen, Felsschluchten, Straßenverläufe und landwirtschaftliche Flächen sind (Kapitel 6.1). Da die verlässliche Quantifizierung von Feuerholzquellen außerhalb von Forstflächen noch eine große Herausforderung darstellt, wurden im zweiten Artikel die Nachfrage und Verfügbarkeit von Feuerholz analysiert. Die Analyse hat ergeben, dass für die meisten untersuchten Flächen das Budget zwischen Angebot und Nachfrage von Feuerholz positiv ist. Jedoch müssen diese Ergebnisse wegen großer Unsicherheiten im Modell mit Vorsicht betrachtet werden (Kapitel 6.2 und 9). Eng mit dem zweiten Artikel verbunden, wurde im dritten Artikel holzige Biomasse mit Hilfe von hochaufgelösten RapidEye Satellitendaten für sieben Forstflächen in der Forschungsregion beziffert. Der Artikel zeigte, dass die Einbringung von Spektralinformation des Bandes Red Edge und Textureigenschaften der multispektralen Bilddaten die Modellergebnisse zur Messung von holziger Biomasse erheblich verbesserten (Kapitel 6.3 und 10). Die Möglichkeiten diese Ergebnisse der Studie in die räumliche Analyse der Nachfrage von Feuerholz einfließen zu lassen wird im Kapitel zu Forschungsausblick diskutiert (Kapitel 13).

Nicht nur die reine Nutzung von Feuerholz, sondern auch die generelle Steuerung, Bewirtschaftung und Kontrolle von Wald sind ein wichtiger Aspekt wenn eine nachhaltige Verfügbarkeit von Ressourcen gegeben sein soll. Der vierte Artikel erfasste somit einen breiteren Einblick in die gegenwärtigen Entwicklungen des Forstsektors in Tadschikistan und inwiefern forstliche Ökosystemdienstleistungen (ÖSL) gestärkt werden. Umfassende und ausführliche Interviews wurden mit Experten auf nationaler Ebene durchgeführt. Die Ergebnisse deuteten darauf hin, dass die Einrichtung von neuen institutionellen Netzwerken momentan zu positiven Entwicklungen im Forstsektor und einer verantwortungsvolleren und besser geregelten Forstwirtschaft führen. Jedoch wurden noch einige Herausforderungen in der Schaffung von gesetzlichen Rahmenbedingungen, Transparenz bei Entscheidungsfindungsprozessen und deren Umsetzungen identifiziert, die es noch zu überwinden gilt (Kapitel 6.4 und 11).

Obgleich diese Dissertation forschungsbedingt noch einige Unsicherheiten und Limitierungen beinhaltet (Kapitel 12 und 13), trägt sie zu neuen empirischen Erkenntnissen bei und verbessert das Verständnis von: i) der Energiesituation, ii) der Rolle von forstlichen ÖSL um den Energiebedarf zu decken, iii) der Situation von Angebot und Nachfrage und iv) der Steuerung und Kontrolle von ÖSL. Zudem sind die Ergebnisse nicht nur für die Hochgebirgsregion Tadschikistans von Relevanz, sondern lassen sich auch auf andere Regionen mit ähnlicher Historie und sozio-ökonomischen Entwicklungen, wie z.B. Nachfolgestaaten der Sowjetunion, sowie ähnlichen klimatischen Bedingungen übertragen. Weitere Forschungsschwerpunkte sollten auf die weitere Erfassung von quantitativen und qualitativen empirischen und ökologischen Daten gelegt werden, um ein besseres Verständnis über Veränderungen in der Verfügbarkeit und im Verbrauch von ÖSL als Lebensgrundlage für die Bevölkerung zu erlangen. Im Hinblick auf klimatische Veränderungen in den vulnerablen Hochgebirgsregionen Zentralasiens ist es anzunehmen, dass die Bedingungen extremer werden. Vor diesem Hintergrund sind Fortschritte in der angewandten Forschung entscheidend, um einen Beitrag zur Verringerung des Nutzungsdrucks auf die ohnehin schon knappen Ressourcen in der Region leisten zu können (Kapitel 13). Forschungsschwerpunkte sollten hierbei die Auswirkungen des Klimawandels auf die Landnutzung sein; die Bereitstellung von multiplen ÖSL; die Entwicklung von Anpassungsstrategien an unzureichender Versorgung von ÖSL; räumliche und zeitliche Versorgung von ÖSL und deren Bereitstellungssynergien sowie – Konflikte; alternative Strategien um die Verfügbarkeit von ÖSL zu erhöhen und gleichzeitig die Nachfrage zu senken.

List of figures

List of tables

List of abbreviations

CEP	Committee on Environmental Protection under the Government of the Republic of Tajikistan
ES	Ecosystem Services
FA	Forestry Agency under the Government of the Republic of Tajikistan
FESP	Framework for Ecosystem Service Provision
GBAO	Gorno Badakhshan Autonomous Oblast
GJ	gigajoules
GoT	Government of Tajikistan
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
JFM	Joint Forest Management
m asl	meter above sea level
MA	Millennium Ecosystem Assessment
MJ	megajoules
NBT	National Bank of Tajikistan
NTFP	Non-timber forest product
SDFH	State Department for Forestry and Hunting
TEEB	The Economics of Ecosystems and Biodiversity
TJS	National currency of Tajikistan
VO	Village Organization

Definitions of key terms

Term	Definition	Source
Biodiversity	"isthe variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within and among species and diversity within and among ecosystems."	MA, 2003
Demand for ecosystem services	"is the sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period."	Burkhard, et al., 2012
Ecosystem	"An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment, interacting as a functional unit. Humans are an integral part of ecosystems."	MA, 2003
Ecosystem function	"An intrinsic ecosystem characteristic related to the set of conditions and processes whereby an ecosystem maintains its integrity (such as primary productivity, food chain, biogeochemical cycles). Ecosystem functions include such processes as decomposition, production, nutrient cycling, and fluxes of nutrients and energy."	MA, 2003
Ecosystem services (more definitions in Table 1)	"The benefits people obtain from ecosystems." These include provisioning, regulating, cultural, and supporting services.	MA, 2003
Ecosystem services: cultural	"Cultural Services include the non-material benefits people obtain from contact with ecosystems. They include aesthetic, spiritual and psychological benefits."	TEEB, 2010
Ecosystem services: habitat or supporting	"Habitat or Supporting Services underpin almost all other services. Ecosystems provide living spaces for plants or animals; they also maintain a diversity of different breeds of plants and animals."	TEEB, 2010
Ecosystem services: provisioning	"Provisioning Services are ecosystem services that describe the material outputs from ecosystems. They include food, water and other resources."	TEEB, 2010

Term	Definition	Source
Ecosystem services: regulating	"Regulating Services are the services that ecosystems provide by acting as regulators e.g. regulating the quality of air and soil or by providing flood and disease control."	TEEB, 2010
Ecosystem services beneficiary	"A stakeholder who benefits directly from a biological or physical resource, ecosystem service, institution, or social system, or someone who is or may be affected positively by a public policy."	Harrington et al., 2010
Ecosystem services provider	"The component populations, communities, functional groups, or trait attributes thereof, as well as abiotic components such as habitat type, that contribute to ecosystem service provision."	Harrington et al., 2010
Firewood (Tajikistan's context)	Firewood: unprocessed woody biomass of trees, bushes, shrubs used for burning mostly for food cooking or house heating.	Authors' definition
Forest (Tajikistan's context)	"Area which is no less than 10% covered by wood-forming plants, not less than 0.5 ha and a width not less than 10 m."	Forest Code, 2011
Forest fund (Tajikistan's context)	"The State Forest Fund comprises of all the forests of natural origin, regardless of the land user, as well as forests of artificial origin, administered by the state agencies, and lands which are not covered with forest vegetation, provided for forestry needs."	Forest Code, 2011
Forest governance	"Forest governance includes the norms, processes, instruments, people, and organizations that control how people interact with forests."	Kishor and Rosenbaum, 2012
Good governance	"Governance is generally considered "good" if it is characterized by stakeholder participation, transparency of decision making, accountability of actors and decision makers, rule of law, and predictability. Good governance is also associated with efficient and effective management of natural, human, and financial resources, and fair and equitable allocation of resources and benefits."	Kishor and Rosenbaum, 2012
Pasture (Tajikistan's context)	"Land of the State Forest Fund intended for livestock grazing purposes."	Forest Code, 2011
Supply of ecosystem services	"refers to the capacity of particular area to provide a specific bundle of ecosystem goods and services within a given time period."	Burkhard, et al., 2012

List of papers and author’s contribution

Paper 1

Title: Factors influencing households' firewood consumption in the western Pamirs, Tajikistan.

Authors: Bunafsha Mislimshoeva, Robert Hable, Manuchehr Fezakov, Cyrus Samimi, Abdulnazar Abdulnazarov, Thomas Koellner

Journal: published in *Mountain Research and Development*, 34(2):147-156.

Own contribution: corresponding author, data collection (100%), data analysis (70%), figures (90%), concept and discussion (80%), writing (90%)

The overall study design was developed by Mislimshoeva and Koellner. Hable contributed to the data analysis and part of the methods writing. Figures and tables were created by Mislimshoeva and Hable. Mislimshoeva wrote the first draft of the manuscript and all co-authors contributed to the revision of the manuscript.

Paper 2

Title: Forest firewood availability and usage: the case of western Pamirs, Tajikistan

Authors: Bunafsha Mislimshoeva, Paul Schumacher, Cyrus Samimi, Thomas Koellner

Journal: planned to submit to *Forest Ecology and Management* journal

Own contribution: corresponding author, data analysis (90%), figures (100%), concept and discussion (75%), writing (100%)

Mislimshoeva, Koellner and Schumacher developed the overall study design. Data analysis, figures and tables were created by Mislimshoeva. The first draft of the manuscript was written by Mislimshoeva and all co-authors edited and gave feedback.

Paper 3

Authors: Paul Schumacher, Bunafsha Mislimshoeva, Alexander Brenning, Harald Zandler, Martin Brandt, Cyrus Samimi, Thomas Koellner

Title: Woody biomass estimation in semi-arid high mountainous region using high-resolution red edge and texture satellite features

Journal: planned to submit to *Remote Sensing* journal

Own contribution: data collection (50%), data analysis (5%), concept and discussion (40%), writing (15%)

The overall study design was developed by Schumacher, supervised by Koellner, Samimi and Mislimshoeva. Schumacher and Mislimshoeva conducted the fieldwork for data collection. Data analysis and was done by Schumacher and supported by Brenning, Zandler and Brandt, who also contributed to the methods part writing. Figures and tables were created by mostly by Schumacher and supported by Zandler. Schumacher wrote the first draft of the manuscript and all co-authors contributed with feedback and revision.

Paper 4

Authors: Bunafsha Mislimshoeva, Peter Herbst, Thomas Koellner

Title: Current pathways towards good forest governance for ecosystem service in the former Soviet republic Tajikistan

Journal: published in *Forest Policy and Economics,* 63, 11-19

Own contribution: corresponding author, data collection (100%), data analysis (100%), figures (100%), concept and discussion (80%), writing (95%)

The overall study design was developed by Mislimshoeva and supervised by Koellner and Herbst. Mislimshoeva conducted all interviews in the study area, analyzed the data, created all figures, and wrote the draft of the manuscript. Koellner and Herbst contributed to the manuscript with feedback and revision.

PART I

CONCEPTUAL FRAMEWORK

1. Thesis motivation and outline

During the past 50 years, a growing population (from 2.5 billion in 1950 to 7.2 billion in 2013) and changing consumption patterns have led to an increasing pressure on the world's natural resources (Tilman et al., 2001; Arrow et al., 2004; Imhoff et al., 2004; Godfray et al., 2010; Liu et al., 2010; Zhen et al., 2011; MA, 2005a, 2005b; UN, 2012, 2013). The growing demand, mostly for food, fresh water, timber, fiber and fuel, results in considerable global changes in the ecosystems (MA, 2005a, 2005b). While technically advanced countries are able to expand their natural limits (Meadows et al., 1972), this knowledge is still limited in most parts of the world. For example, most developing countries with weak economies depend heavily on the availability of natural resources and, consequently, their ecosystem services (ES). This is particularly the case in the context of forests related to energy consumption. As one of the most important provisioning services, firewood is harvested from forests but also from trees growing outside of forests and remains the main domestic fuel source for rural populations in developing countries (Kersten et al., 1998; Mahapatra and Mitchell, 1999; Okello et al., 2001; Arnold and Persson, 2003; Angelsen and Wunder, 2003; Arnold et al., 2006).

Depending on the scale, forest firewood supply and demand are not entirely uniform and vary from country to country and region to region (Drigo et al., 2002; Arnold and Persson, 2003; Angelsen and Wunder, 2003; Parikka, 2004). The distribution of forest goods and services is highly dependent on the governance at spatial and temporal scales. Currently, forest governance has three main trends: a) decentralized management of forests that are not relevant for logging but play an essential role in rural areas of developing countries, b) involvement of logging companies, and c) certification system, especially in developed countries (Agrawal et al., 2008). Many developing countries, especially those located in the high mountainous plateau of Central Asia, relate only partly to the first category of the classification by Agrawal et al., (2008), because decentralized management of forests is yet to be achieved in this region. The region is not unique by its landscape characteristics only, but also due to its distinctive history as a part the Soviet Union from the 1920s to the 1990s. At present, all Central Asian countries are facing a transition from a communist command-and-control system to a more market oriented, decentralized and participatory forestry. Moreover, the energy crisis, which occurred after the collapse of the Soviet Union put high pressure on the already scarce forest resources.

Against these global and regional backgrounds, this research focuses on understanding energy consumption patterns, forest firewood supply, demand and governance at the local and national scales. Empirical case studies are demonstrated in the case of Tajikistan, one of the Central Asian developing countries in transition. The outline of the thesis is presented in Figure 1.

PART I highlights a critical review of theories on the ES concept, followed by a focus on forest ES and their role in the context of developing countries. The thesis then narrows to developing countries of the former Soviet Union, describing their distinct historical background of energy situation and forest governance. Within these countries, the chapter narrows to the mountainous regions of Tajikistan, which are especially vulnerable due to their scarce energy resources. This is followed by establishing a research niche and objectives of the study. The research area and a short overview of the methodological steps are also described in this chapter as well. A detailed explanation of the methods and data is included in the summary of each research paper at the end of this chapter. PART II introduces the research papers of the thesis. PART III summarizes the main conclusions and gives relevant recommendations for different stakeholders

.

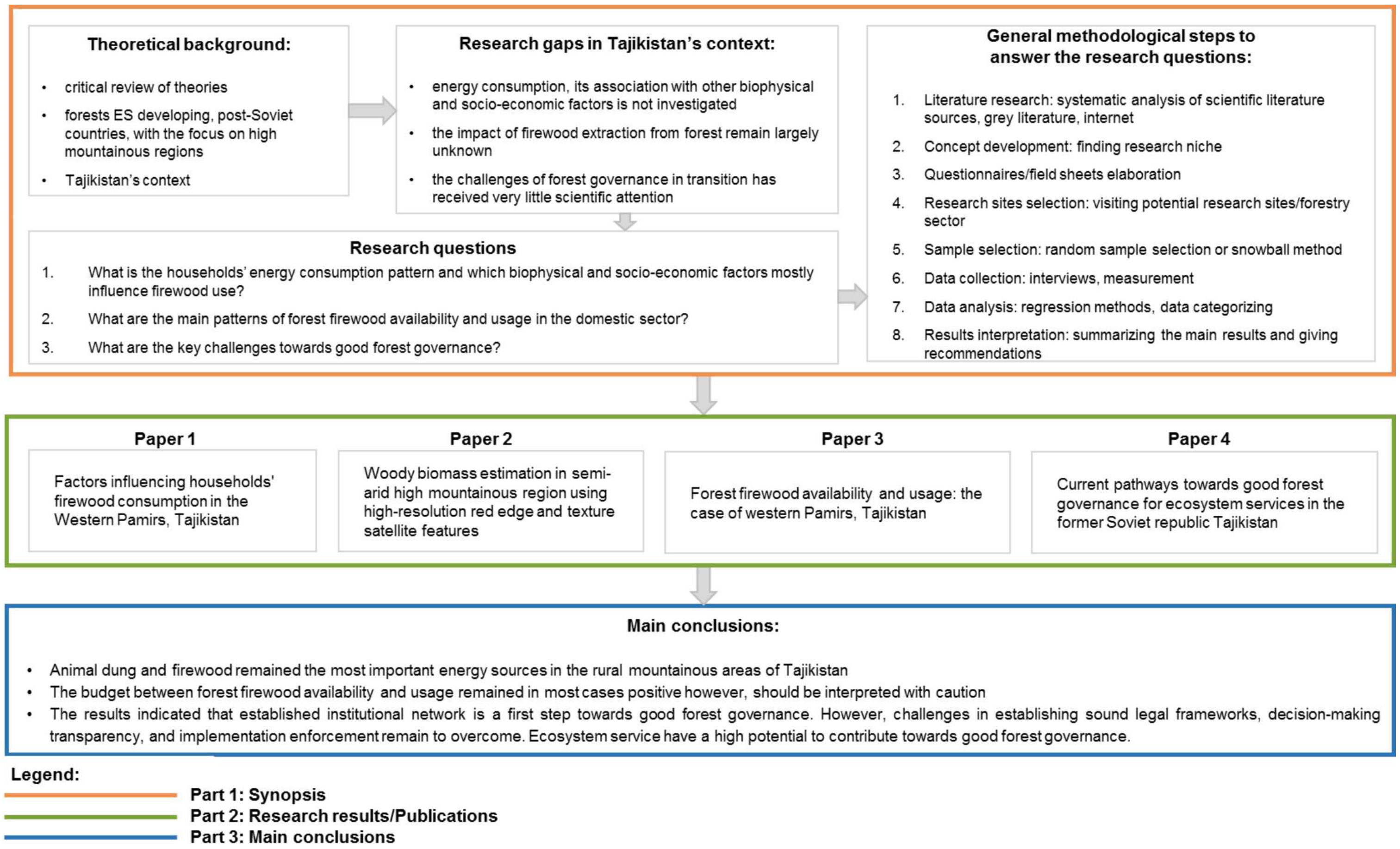


Figure 1 Outline of the thesis.

2. Research framework

2.1 Ecosystem services concept: from a metaphor to scientific framework

The current concept of 'Ecosystem Services' and the economic valuation of these services are the results of half a century of debates among scientists, politicians and practitioners (e.g. Krutilla, 1967; Ronald et al, 1969; Helliwell, 1969; Ehrlich et al., 1977; Randall and Castle, 1985; Costanza, 1991; de Groot, 1992; Pearce and Moran, 1994; Daily, 1997; Daily et al., 2000; de Groot et al., 2002). Ecological economists and conservation biologists promoted the metaphor of viewing nature as a stock of "capital" in order to communicate the economic growth, environmental sustainability and nature conservation (Costanza and Daly, 1992; Daily, 1997; Jansson et al., 1994; Prugh et al., 1999; Daily et al., 2000). The relationship between the economy and the natural environment became stronger, resulting in the creation of an integrating discipline called 'ecological-economics' in the 1990s (Costanza, 1991; Braat and de Groot, 2012). The "eye-opening" metaphor used in that context soon turned into a framework, leading to the foundation of the Millennium Ecosystem Assessment (MA) in 2003, in order to create a holistic, science based and policy-relevant platform (Norgaard, 2010; MA, 2003, 2005a). The transition was complemented by diverse, multilevel, theoretical and practical concepts as well as the development of new monetary valuation methodologies of nature, which resulted in an exponential growth of scientific literature (Fisher et al., 2009).

In contrast, the controversy sparked by the economic valuation of ES received much criticism (see e.g. Chee, 2004; Sagoff, 2008; Gómez-Baggethun and Ruiz-Pérez, 2011; Norgaard, 2010; Schröter et al, 2014). Grêt-Regamey et al., (2012) claims the ES concept to have been misused and reduced to "a buzzword", and thus being at risk of dying off. Nevertheless, the MA and the promising methods for monetary valuation of nature led to the establishment of the global initiative – The Economics of Ecosystems and Biodiversity (TEEB), which is focused on highlighting the growing cost of biodiversity loss and ecosystem degradation (TEEB, 2010). Following TEEB, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012 aiming for a more effective use of science in practical decision-making at all scales (IPBES, 2012). In parallel, a distinct Ecosystem Services Journal is now devoted to these topics alone. ES in general represents an important area of research at present due to the increasing destruction of ecosystems globally (Fisher et al., 2009; Patterson and Coelho, 2009).

Considering the frequent appearance of ES in scientific literature, there seems to be no agreement on a consistent definition of ES (de Groot et al., 2002; Kline, 2007; Costanza, 2008; Fisher and Turner, 2008; Patterson and Coelho, 2009; Fisher et al., 2009). Each definition differs according to its emphasis on the supply and/or demand side, market and non-market services, temporal and spatial scale, units of measurement, policy relevance and so forth (Patterson and Coelho, 2009). Depending on the aim of each specific study, many other definitions evolved in the past decades. Table 1 presents an overview of the most common ES definitions in research and practical application. The most generic and accepted definition of ES remains "the benefits that people receive from healthy ecosystems" (Daily, 1997; MA, 2003). As it is broad, this definition allows meaningful comparisons across different policy contexts, temporal and spatial scales. The definition is, however, debatable especially when considering arguments from ecology and economics perspectives. The distinction between goods (e.g. food) and services (e.g. aesthetic values) is sometimes made, but not always (Fisher et al., 2009; Braat and de Groot, 2012). However, up to now the concept remains the most generic, scientifically accepted and with great potential for practical applications.

Table 1 Multiple definitions of ecosystem services in research and practical application (adapted from Patterson and Coelho, 2008; Braat and de Groot, 2012).

Definition	Source(s)
"Ecosystem Services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life"	Daily, 1997
"Ecosystem Services are the benefits human populations derive, directly or indirectly, from ecosystem functions"	Costanza et al., 1997
"Ecosystem Services are the benefits people obtain from ecosystems"	Daily, 1997; MEA, 2003;
"Ecosystem Services are components of nature, directly enjoyed, consumed, or used to yield human well-being"	Boyd and Banzhaf, 2007
"Ecosystem services include ecosystem organization (structure), operation (process), and outflows, if they are consumed or utilized by humanity either directly or indirectly"	Fischer et al., 2008; Fischer et al., 2009
"Ecosystem Services are the direct and indirect contributions of ecosystems to human well-being"	TEEB, 2010

2.2 Conceptualizing ecosystem services supply and demand

Although the growing demand for many ES is compensated by increasing supply, currently human well-being is affected by the gap between ES supply and demand (MA, 2003, 2005b). In recent years, many studies have attempted to quantify demand and/or supply of various ES. Researchers have generally focused on the supply analysis across various scales (Antle and Valdivia, 2006; Egoh et al., 2008; Jujnovsky et al., 2012), while less attempts have been made to analyze the demand side (Ferng, 2007). Some have spatially quantified the demand and supply of specific ES simultaneously (Top et al., 2004; Masera et al., 2006; Ghilardi et al., 2009; McDonald, 2009; Raudsepp-Hearne et al., 2010; Nedkov and Burkhard, 2011; Burkhard et al., 2012). Further studies have conceptualized the ES supply and demand interrelation. Koellner (2009) proposed an outstanding ES supply and demand concept in the context of nature and human well-being, showing the interdependences between the ecological and the socio-economic system. Similarly, Burkhard et al., (2012) developed a conceptual framework linking ecosystem integrity, ES and human well-being with supply and demand in the human-environmental system. Paetzold et al., (2010) suggested a framework to assess ecological quality taking into account the demand and supply of ES. Another recent Framework for Ecosystem Service Provision (FESP) suggested by Rounsevell et al., (2010) addresses the role of humans within various components in the socio-ecological system. This framework also underlines the conflicts and trade-offs between multiple ES as well as providers and beneficiaries of ES.

However, there is a lack of a conceptual framework that goes beyond the supply and demand of ES and addresses the mechanism of their interrelation as well as strategies to overcome scenarios where the demand exceeds the supply. Figure 2 depicts a conceptual framework integrating the relationship between demand and supply for ES, including emerging scenarios across multiple scales. Two general strategies can be applied: the first one is to decrease the demand and the second is to increase the supply of the given ES. Both strategies in turn consist of actions. On the one side, the fact that an ecosystem provides multiple and interrelated services is often overlooked, thus leading to an increase of few services, but at the same time to a decline or loss of other services (Bennett et al., 2009). On the other side, to capture all ES across all scales is unfeasible. Therefore, the supply and demand of only one ES (ES_1) is demonstrated in the framework below. The ES supply and demand can be influenced by biophysical, socio-economic factors and governance of resources across multiple scales.

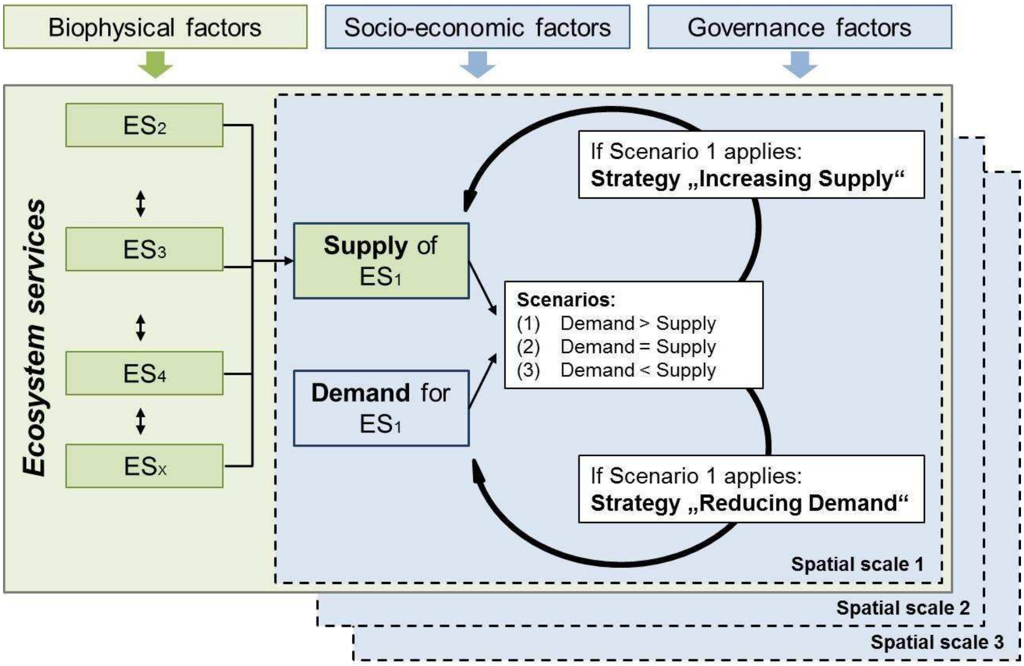


Figure 2 General framework showing the scenarios of ES1 and the strategies. The application of any strategy has a feedback-loop effect on the ES1 over time. Thus, a change in the supply of ES1 in turn has an effect on the other ES. The demand and supply of ES, the scenarios and strategies are influenced by interacting biophysical, socio-economic and governance factors at multiple spatial scales.

2.3 Governance of forests and their ecosystem services

In line with the current worldwide deforestation and other environmental changes related to forests, the forest governance topic lately received much scientific and political attention. While the issue of why some forests are in better condition than others requires further research, there is a general consensus that governance plays a key role in defining forest outcomes (Ostrom, 1999; Tucker, 2010). There is no single accepted definition of forest governance (FAO, 2010; Secco et al, 2013). However, in a broad sense, it includes a "process of how decisions are made about forests, as opposed to focusing exclusively on what decisions are made or the outcomes of those decisions" (WRI, 2013; FAO, 2010). When these outcomes lead to sustainable forest management over a long time, the forest governance is labeled as 'good forest governance.' Similarly to forest governance, there are several definitions of good forest governance. Essentially it includes compliance with the rule of law, effectiveness, transparency, predictability and accountability (FAO and ITTO, 2009; Cashore, 2009a, 2009b; Rametsteiner, 2009; Kishor and Rosenbaum, 2012). These mentioned principles are widely accepted; however, why and how to measure them remains a challenge (Kishor and Rosenbaum, 2012; WRI, 2013;

Secco et al., 2013). The reason to measure forest governance principles is that "it is easier to manage things that can be measured" (WRI, 2013) and it "provides foundation for improvement" (Cashore, 2009b; Kishor and Rosenbaum, 2012). The answer to the 'how' question is, however, not so simple. Measurement of "goodness" or "badness" of forest governance has not been an easy task for scientists, politicians and practitioners, because quantitative assessments are difficult and qualitative ones are subjective (WRI, 2013). Nevertheless, several methodologies and tools were developed in order to assess forest governance at international and national scales (Secco et al., 2013). Approaches such as the Ministerial Conference on the Protection of Forest in Europe set of Criteria and Indicators (MCFPE, 2015), the Forest Law Enforcement, Governance and Trade (FLEGT, 2015) and tools like Forest Governance Diagnostics Tool (WB-ARD, 2009), Governance of Forests Toolkit (GFI, 2009) and Framework for Assessing and Monitoring Forest Governance (Kishor and Rosenbaum, 2012) are already implemented on global, regional and national levels. As for the sub-national or local levels, Secco et al., (2013) developed a comprehensive set of indicators for assessing forest governance.

2.4 Forest ecosystem services in developing-transition countries

Forest ecosystems are a central component of Earth's biogeochemical systems. They provide crucial ecosystem functions, goods and services for human well-being in multidimensional ways (MA, 2005a; Nadrowski et al., 2010; Amacher et al., 2014). Until recently, timber production was the main objective of forestry, though other ES are attaining similar importance (Aldea et al., 2014). ES are classified into four categories, which apply to forest ecosystems as follows (MA, 2005; Patterson and Coelho, 2009; UN, 2014):

- Provisioning: physical products of forests (e.g. food, wood, and fuel);
- Regulating: the 'preventative' benefits of forests (e.g. erosion control, regional climate regulation, carbon sequestration);
- Cultural: nonmaterial benefits of forests (e.g. aesthetic, spiritual, and recreation);
- Supporting: foundations of all other ES of forests (e.g. nutrient cycling, water cycling, and provisioning of habitat).

The above mentioned forest ES are fundamental for the survival of local people, especially in developing countries, which are characterized by relatively little capital (MA, 2005b; Vemuri, 2008; Ferraro et al., 2011). While forest-rich developing countries (e.g. tropical areas) have received worldwide attention because of their economic value, biodiversity and broad range of services, forest-poor countries (e.g. in arid areas) are often overlooked across international science-policy agendas. This is especially true for mountainous areas of developing countries where forest resources are very scarce, but where the local population is particularly dependent on these resources. At the same time mountainous regions are vulnerable due to their geographical isolation and threats of the impact of global changes (Koellner, 2009; Grêt–Regamey et al., 2012; Briner et al., 2013). Furthermore, some mountainous regions are strongly influenced by the history of forest governance.

3. Research gaps

In recent years, especially after the creation of the Millennium Ecosystem Assessment (2003), worldwide research on forest ES has increased drastically (Figure 3). While China plays a leading role among developing countries in forest ES research, many other countries failed to deliver adequate information and "responses to the challenges of sustainable forest development in a rapidly changing world" (Acharya, 2005). This is because forestry research is expensive and some developing countries are not yet able to afford establishing a sound research platform. This is especially noticeable in the Post-Soviet developing countries. Before the collapse of the Soviet Union, much funding was invested in forestry research, but since the collapse there have only been little investments in forest related studies. A further barrier is that literature from Soviet times is only available in Russian language and accessible in the archives or libraries with a lack of digital access. Thus, the knowledge about important forest ecosystem goods, such as fuel and services, erosion prevention and water quality is currently very limited.

A big share of energy originates from forests. The rising concern of lack of energy sources and thus, sustainable management of forests resources, remains a crucial issue in the isolated mountainous regions. Tajikistan, a post-Soviet mountainous republic received very little attention of science based approaches in the field of energy use and resources governance. Despite the importance of scarce energy sources in the daily life of people in Tajikistan, very few empirical studies exist. Furthermore, understanding of energy sources, such as firewood extraction from the forests, is very limited. This is particularly important for mountainous areas of Tajikistan due to their remoteness, socio-economic conditions and limited access to alternative energy sources. Understanding forest firewood production and consumption patterns is crucial for sustainable forest management, as it allows this scarce resource to be allocated efficiently. Currently, the impact of firewood extraction from forest remains largely unknown. Methodologically, to estimate forest above ground biomass in arid environments different techniques have been applied to low and medium resolution satellite images (Diouf and Lambin, 2001; Kraus and Samimi, 2002; Qi and Wallace, 2002; Wiley et al., 2002; Holm et al., 2003; Samimi, 2003; Samimi and Kraus, 2004; Kawamura et al., 2005; Wessels et al., 2006; Aranha et al., 2008; Xu et al., 2013; Brandt et al., 2014). However, a large scientific gap remains in high arid mountainous areas, such as the Central Asia region, where high resolution imagery ($\leq$ 5 m), including red edge band or texture parameters, has so far not been used.

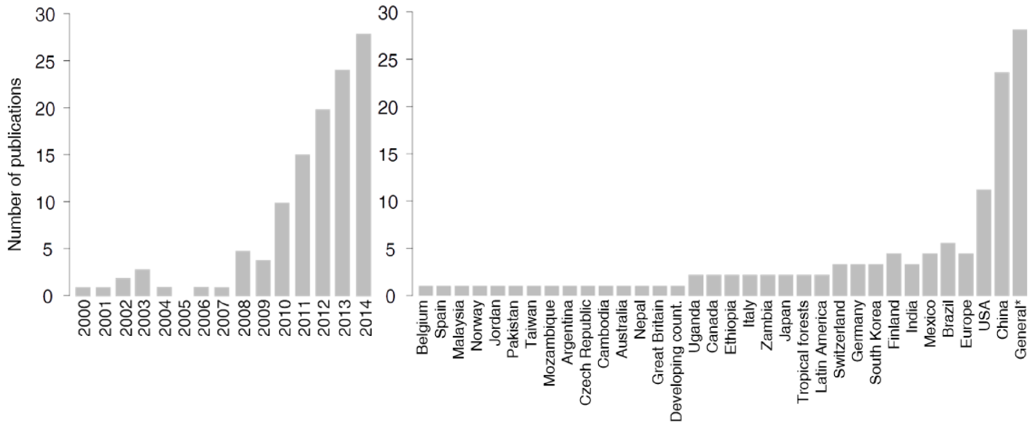


Figure 3 Number of publications using the term "forest" AND "ecosystem services"; "forest" AND "ecological services" in an ISI Web of Science search from 1998 to 2014 in the title. a) publications sorted according to the year; b) publications sorted according to country/region. *reviews, concepts, methodological papers.

4. Aims and research questions

Given the background and research gaps elaborated above, this research aims to attain a broader understanding of the domestic energy consumption in rural areas, with a special focus on forest firewood use and forest governance related to challenges towards good governance. Tajikistan, as an example of high arid-mountainous regions and countries in transition, is chosen as a case study area, for which this comprehensive aim is scaled down to two main hypotheses:

Hypothesis 1: Since the collapse of the Soviet Union, firewood remains a particularly important source of energy in the rural mountainous regions of Tajikistan.

Out of the eight million Tajikistan's inhabitants, 73% live in rural areas (World Bank, 2014a; 2014b). However, rural population consumes only 8-11% of the total electricity (UN, 2013). Until now, most of the efforts on promoting energy result in estimating the potential for hydro, solar and wind energy, while the rural population continues to suffer from energy poverty, especially in winters. Moreover, 55% of the rural population lives below the national poverty line (US$ 1.4 per capita per day) (World Bank, 2009). Thus, because of the high prices of coal and gas (due to the long transportation distance) and electricity, in many mountainous places local people prefer the cost-effective option of collecting firewood from their own gardens, or along the roads, fields, in the mountains and are also known to extract it legally/illegally from forests. Apart from the local energy situation in Tajikistan, our hypothesis is supported by numerous publications, stating the importance of firewood use in developing counties and mountainous regions (e.g. Kersten et al., 1998; Mahapatra and Mitchell, 1999; Okello et al., 2001; Arnold and Persson, 2003; Angelsen and Wunder, 2003; Arnold et al., 2006).

Hypothesis 2: Major challenges are yet to be overcome to achieve good governance of forests in Tajikistan.

Although the forested area in Tajikistan were relatively small, during the Soviet times (and still are), the forest sector was very powerful in terms of management, control, finance and technology. As forests belonged to the socialistic state (Mukhin and Kryvda, 1976), the state played the dominant role in defining policy directions and invested large funds in the development of the sector (Lazdinis et al., 2009). However, currently, as Tajikistan is passing through the transition phase towards a market-oriented economy, and as the contribution of forests to the economy is not recognized, very limited funds are allocated to the forest sector. There is an absence of stable financial revenue, e.g. no well-established markets for forest products are available (Kirchhoff and Fabian, 2010). This allows hypothesizing that there is lack of personnel, technology and other challenges for the forest sector in order to achieve good forest governance.

These two hypotheses led to the development of **three main research questions** framing the present thesis:

1. What is the households' energy consumption pattern, and which biophysical and socio-economic factors mostly influence firewood use?
2. What are the main patterns of forest firewood supply and demand in the domestic sector?
3. What are the key challenges towards good forest governance?

These research questions are highlighted shortly in chapter 6 in the summary of the main results and fully addressed in the research papers in PART II.

5. Research area

5.1 Physical characteristics

The research area is Tajikistan with a total area of 143,100 km², of which around 93% is covered by high mountains, while almost 50% of the area is located at an elevation of more than 3000 masl (Romer, 2005; UNDP, 2008). The climate of the country encompasses zones with continental, subtropical, semiarid and arid climate. It varies considerably with the altitudinal gradient. In the south-western parts the average temperature ranges from 23 °C to 30 °C in July and from 1 °C to 3 °C in January, whereas in the Eastern Pamirs the average July temperature varies between 8 °C and 12 °C. Here, January's absolute minimum temperature can reach -40 °C to -45 °C (UNDP, 2008; Kirchhoff and Fabian, 2010; Vanselow, 2011).

For quantification of energy demand and forest ES, the main focus of this thesis was in the western part of Gorno Badakhshan Autonomous Oblast (GBAO) (also called the Western Pamirs), an arid and high mountainous region (Figure 4). It occupies 63,700 km², which is 44.6 % of Tajikistan's territory. The highest peaks reach up to 7,500 masl. (Breu and Hurni, 2003). The high altitude has a direct impact on the climate in the region. The ranges of the high mountains - Hindukush and Himalaya form a barrier against moisture from the Indian and Atlantic Oceans, thus shaping a continental climate in the region (Miehe et al., 2001; Breckle and Wucherer, 2006). It is characterized by lower temperatures and dry air. The considerable dryness is caused by the remoteness of this region from oceans and large surface waters. The Western Pamirs consist of rocky outcrops very steep slopes and deeply incised valleys along the river Panj. It is administratively divided into seven districts: Darvaz, Vanj, Rushan, Shugnan, Roshtkala, Ishkashim and Murgab.

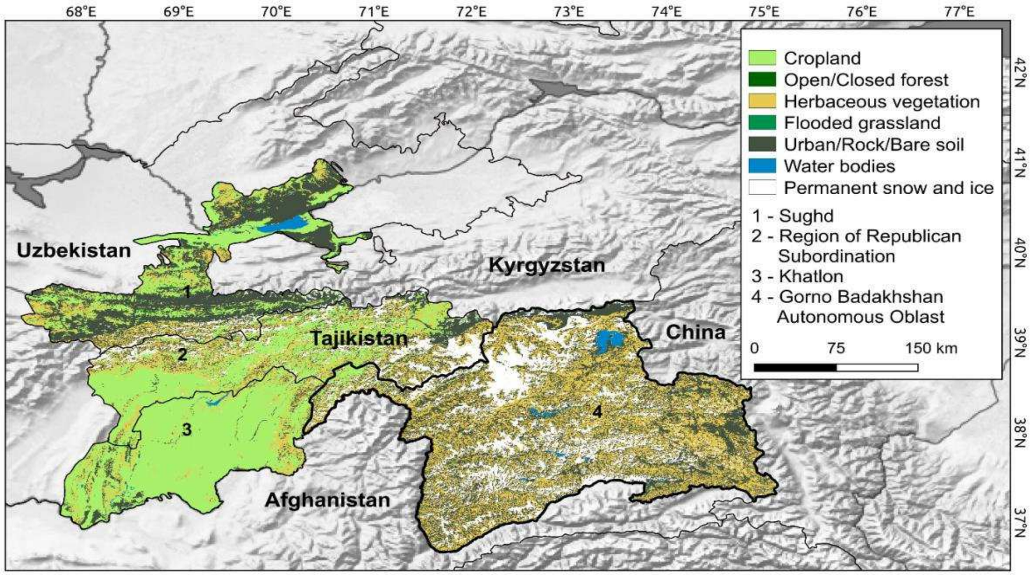


Figure 4 Map of the research area. Land cover classes are based on Globcover, 2009 (base map source: Bicheron et al., 2008).

5.2 Socio-economic characteristics

In 1991 Tajikistan gained independence after the collapse of the Soviet Union. One year later, a civil war caused tremendous human losses and devastated the economy. Even though the economy has grown fast since then, it remains unstable and susceptible. A big share of the economy is reliance on the remittances from labor migrants from abroad. In 2008 the remittances comprised approximately 50% of the country's GDP. The economy is also dependent on exports of cotton and aluminum (UNDP, 2008; World Bank, 2009; ADB, 2014). Tajikistan remains the poorest country in the former Soviet bloc. According to the World Bank (2009), poverty headcount ratio at national poverty line (US$ 1.4 per capita per day) is 47% of the population. Of the eight million inhabitants, 73% live in rural areas (World Bank, 2014a; 2014b).

The collapse of the Soviet Union affected all levels of society in the Tajik Pamirs, as the external supply of resources, goods and services ended abruptly (Herbers, 2001; Nijozmamadov, 2005). The situation became more tragic by the inflow of 55,000 refugees into GBAO during the subsequent civil war (Droux and Hoeck, 2005). Humanitarian aid was provided by international organizations in order to prevent a humanitarian disaster in the region (Breu and Hurni, 2003). Farming and livestock breeding are the main occupations of the local population. In spite of many rivers and rivulets, people struggle to bring sufficient water to the agricultural land due to a lack of appropriate techniques.

5.3 Energy sources and use

During the Soviet time, Tajikistan relied on local energy but also greatly on imports of electricity (natural gas and coal). Especially in winter, as domestic energy demand was high, Tajikistan imported electricity from Turkmenistan and Uzbekistan, natural gas from Uzbekistan and Turkmenistan, and coal mostly from the Kyrgyz Republic. Since the collapse of the Soviet Union, and during the civil war, the energy supply network collapsed. It recovered partly in the early 2000s, coinciding, however, with significant increases in prices, affecting in particular low income households (World Bank, 2014c).

Disputes (over sharing of water resources) led to the deterioration of political relations with Uzbekistan, resulting in a permanent termination of imports of gas and electricity from Uzbekistan in 2012. Currently gas is imported from Kazakhstan. Coal, originating from within Tajikistan (partly also imported from Kyrgyz Republic) still reaches rural areas and small towns. The prices vary widely due to differences in transportation costs and seasonal availability. Firewood, animal dung, and cotton stalks are available locally and widely used in order to supplement coal in winter (World Bank, 2014c).

Increased prices of energy sources and their influence on the households' expenditure are alarming. In rural areas, households spend on average around 10-15% of their total consumption on energy, while a fifth of the population spends 19-24% during the heating season. This is much more than the 10% 'energy poverty' marks according to the World Bank (2014).

Energy use is extremely diverse. It differs between cities and rural areas, provinces, household income levels and seasons (for full analysis see World Bank, 2014c). For example, urban apartments use electricity for all needs, while in rural areas energy consumption is covered largely by firewood, dung, and coal. In GBAO's rural areas in particular, firewood and animal dung play an important role (World Bank, 2014c). Thus, a general estimation of energy consumption seems to be challenging. Although prices of energy sources can also vary strongly, some averages can be calculated (Table 2).

Table 2 Average energy sources prices in Tajikistan (World Bank, 2014c; Asia-plus, 2015)

Energy source	Unit	Average price
Electricity	kWh	TJS 0.13 (US$ 0.02) for residents TJS 0.31 (US$ 0.06) for enterprises
Firewood	bundle	TJS 10 - 15 (US$ 2.1 - 3.15)
Animal dung	kg	not available
Coal	kg	TJS 1.40 (US$ 0.3)
Gas	Kg	TJS 5 (US$ 1.05)

5.4 Forest resources and their governance

Due to the lack of forest inventories in the last 30 years, no reliable data on forest cover is available. According to the Global Forest Resources Assessment estimates (2010), the State Forest Fund encompasses 1.8 million ha (around 12% of Tajikistan's territory), out of which approximately 410,000 ha (around 3% of total area) are actually covered by forests. Other sources estimated that due to the ongoing human-induced degradation, less than 2% of the total area is covered by forests (Kirchhoff and Fabian, 2010).

Forest resources of Tajikistan provide manifold important ecosystem goods (e.g. wood, nuts) and services (e.g. water filtration, erosion prevention) and are a crucial hotspot of biodiversity in the region. Approximately 200 different species of trees and shrubs can be found, including rare and endangered species in the forests (Kirchhoff and Fabian, 2010). The most widespread types of forests in Tajikistan are coniferous forests (*juniperus*), broadleaved forests (*mesophilous),* small-leaved mountain forests (*microthermous),* light forests (*Xerophilous*), and *Tugai* forests (Novikov and Safarov, 2003; Kirchhoff and Fabian, 2010).

Coniferous forests occupy the largest area compared to other types of forests in Tajikistan. They are dominated by conifer species such as *Juniperus sibirica*, *J. turkestanica*, *J. Seravschanica*, *J. semiglobosa*, and *J. schugnanica*. Juniper forests grow on altitudes from 2,500 (Ahmadov, 2005) to 3,700 masl with an average wood volume of 10 to 120 m^3/ha. Junipers play a very important role in decreasing landslide risk and water regulation on steep slopes (Novikov and Safarov, 2003).

Broad-leaf forests are located at altitudes from 1,200 to 2,500 masl and consist mainly of *Juglans regia*, *Malus sp.*, *Acer regeli*, *A. turkestanicus* and *Platanus orientalis*. Broad-leaf forests are rich in biodiversity. More than 40 species of mammals, 200 species of birds and 10 species of reptiles inhabit these forests, and the average wood volume is estimated to be at 90 m^3/ha (Novikov and Safarov, 2003).

Small-leaved forests in the research area (also known as riparian forests or floodplain forests) are found in the floodplains of the river banks in higher elevations from 1,500 masl (Akhmadov, 2008; Kirchhoff and Fabian, 2010) to approximately 3000 masl (Figure 5). The average wood volume of small-leaved forests is about 60-150 m^3 per hectare (Novikov and Safarov, 2003). The main species growing in these forests are willow (*Salix turanica, Salix shugnanica, Salix wilhelmsiana and Salix babylonica*), poplar (*Populus pyramydalis and Populus pamirica*), tamarix (*Tamarix*), barberries (*Berberis vulgaris*), wild rose (*Rosa canina*) and sea-buckthorn (*Hippophae rhamnoides*).

Figure 5 Riparian forests in the Western Pamirs, Ishkashim district. Photos: Mislimshoeva, 2013.

Xerophytic light forests are known as *Shibliak.* Theyare characterized by communities of deciduous trees and shrubs. The *Shibliak* canopies in Tajikistan are dominated by the species *Amygdalus bucharica*, *Pistacia vera*, *Calophaca grandiflora*, *Cercis Griffithii*, *Rhus coriaria*, *Zizyphus jujuba* and others (Ahmadov, 2008). These forests are spread at elevations from 600 to 1,700 masl. Average wood volume of *shibliak* forests is 3-12 m^3/ha. Average pistachio productivity makes up 70-300 kg/ha (Novikov and Safarov, 2003). According to the Tajik-Pamirs expedition held in 1932, the area of light forests was estimated at 170 thousand hectares, which at present decreased to 80-90 thousand hectares.

Tugai forests consist of poplar *Populus pruinosa*, oleaster *Elaeagnus oxycarpa* and tamarisk *Tamarix laxa.* They are usually combined with reed grass, liana, bulrush and other plant species. *Tugai* forests grow in the flooded lowlands of

Tajikistan alongside riverbanks and islands at elevations from 300 to 600 masl. (Novikov and Safarov, 2003). In the nineteenth century *tugai* forest covered roughlyone million hectares in Tajikistan. Due to conversion to agricultural land and cotton fields, the area of *tugai* has been reduced to around 120,000 ha, which means that almost 90% has been lost over the past 100 years (Ahmadov, 2008).

Almost all forests in Tajikistan belong to the state, forming the State Forest Fund, which is managed by the Forestry Agency (FA) under the Government of the Republic of Tajikistan. An extremely small share is owned by communities and private legal persons. According to the Forest Code of Tajikistan (2011), the state forests are conserved and utilized for a set of ecosystem goods and services (such as non-timber forest products, fuelwood). Conservation and utilization of forest resources is implemented through two main management approaches - Soviet system (permanent foresters) and the Joint Forest Management (JFM) approach (local population involvement; a full description of JFM can be found in Mislimshoeva et al., 2013).

6. Main results summary

In order to quantify forest firewood supply and demand, understanding the energy consumption patterns is essential, because households' firewood usage is linked to the availability of other energy sources. The first paper focuses on the quantification of household energy consumption and improving the overall understanding thereof by assessing total firewood consumption and its influencing factors. Quantification of total firewood in the first paper serves as a basis for the second paper. In the second paper, forest firewood consumption is extracted from the overall amount and related to the supply from forests. In this paper the main focus is put on forest use as a source of firewood. Forest biomass in turn is estimated in the third paper, and closely related to the second paper. The fourth paper not only focuses on forest firewood management, but captures a broader picture of opportunities and challenges of forest governance in Tajikistan and the enhancement of forest ecosystem services.

6.1 Paper 1

Factors influencing households' firewood consumption in the Western Pamirs, Tajikistan

Background: With a growing population, the increasing demand for energy puts high pressure on natural resources, especially in high mountainous regions in developing countries, where other energy sources are limited. Due to the historical background, the energy situation in the mountainous regions of Tajikistan is of special interest. At the end of June 1920, the Soviet system was affirmed in the Tajik Pamirs. The Central Committee of the Communist Party of the Soviet Union declared the Gorno Badakhshan Autonomous Oblast (the Tajik Pamirs) as a part of Tajik Autonomous Soviet Socialist Republic in 1925 (Iskandarov, 2008). The isolation of the region and the transportation represented the main challenges. Thus, between 1932 and 1940, the roads Dushanbe – Khorog and Khorog – Osh were opened, which made it possible to import goods (oil, gas, coal, and kerosene) into the region (Zibung, 2003; Muhabbatov and Khonaliev, 2005). Small-scale household agriculture was replaced by massive industrial production via collectivization and mechanization (Kassam, 2009). The external supply abruptly stopped in 1991 after the collapse of the Soviet Union, which severely affected the Tajik Pamirs (Herbers, 2001; Nijozmamadov, 2005). During the subsequent civil war (1992-97), the situation was aggravated by the inflow of 55,000 refugees into the region (Droux and Hoeck, 2005). Aid had to be provided by international organizations in order to prevent a humanitarian disaster (Breu and Hurni, 2003). Absence of energy supply led to an enormous rise in demand for firewood and animal dung for cooking and heating – a demand which has subsisted until today. Despite the importance of different energy sources in the daily lives of people in the Western Pamirs, very few empirical studies on energy consumption are available (see Hoeck et al., 2007). Furthermore, quantification of firewood use is lacking and no attempts have been made to quantify the association between firewood consumption and influencing factors.

Aim: The aim was to gain understanding of the extent and patterns of household energy consumption, especially firewood and and the factors influencing its usage.

Location: Tajikistan, Gorno Badakhshan, Ishkashim district.

Spatial and temporal scales: eight case studies, winter 2011-12.

Methods and data: Eight villages were selected as case studies in Ishkashim district of the Western Pamirs based on the number of households, available energy sources and duration of heating season. Nearly 40% of the total households in the village were selected for interviews using simple random sampling method. Questionnaire-based interviews were conducted in 170 households to collect information on demographic and socioeconomic characteristics, property, house and heating infrastructure, and energy use. Different energy units (of firewood, animal dung, electricity and coal) were converted to megajoules (MJ) for direct comparison. As the number of independent variables was very high, LASSO regression was used in order to select the most influential variables on firewood consumption (Friedman et al., 2010; 2012). All variables that were non-influential were removed from the analysis and the effect coefficients of the remaining variables were estimated by ordinary least-squares regression and validated by a 10-fold cross-validation.

Results: The results show that households used an average of 9095 MJ of animal dung energy, 5329 MJ of firewood energy, 911 MJ electricity and 187 MJ coal energy per month during winter. Average total annual energy consumption was 86 gigajoules (GJ) per household and 17 GJ per person. As energy consumption is very site specific, it is challenging to directly compare these findings with those of other studies. Nevertheless, similar energy consumption patterns can be observed in other comparable regions (for example, see Samant et al., 2000; Bhatt and Sachan, 2004; Hoeck et al., 2007; SEEDS, 2008; Sharma et al., 2009; Singh et al., 2010; Démurger and Fournier, 2011; Rehnus et al., 2013). Firewood consumption was positively related to elevation, size of a household's private garden and total hours of heating,but negatively related to education level and access to a reliable supply of electricity. Other studies in other regions have explored different relationships between firewood consumption and factors such as income, family size, number of heated rooms, price of firewood and climate (Kennes et al., 1984; Dunkerley et al., 1990; Mahapatra and Mitchell 1999; Bhatt and Sachan, 2004; Johnson and Bryden, 2012; Onoja, 2012; San et al., 2012; Song et al., 2012; Rehnus et al., 2013).

Main conclusions: Findings from this study concluded that rural villages in the Western Pamirs depend heavily on animal dung and firewood for winter heating. Elevation, size of a household's private garden and total hours of heating are positively influencing firewood consumption, while education level and access to a reliable supply of electricity showed a negative influence.

6.2 Paper 2

Forest firewood availability and usage: the case of western Pamirs, Tajikistan

Background: Firewood is one of the most important provisioning services of forests, especially in developing countries (Kersten et al., 1998; Mahapatra and Mitchell, 1999; Okello et al., 2001; Arnold and Persson, 2003; Angelsen and Wunder, 2003; Arnold et al., 2006). On regional and global scales, some broadly aggregated information is available. However, at the national and local scales, firewood consumption is unknown in many countries for various reasons (e.g. lack of funding). In the former Soviet republics of developing countries, quantification of forest firewood availability and usage is of particular interest. In Soviet times, there was almost no demand for forest firewood, while its availability and usage were well documented. However, after the collapse of the Soviet Union, the dependency on local energy sources increased enormously, yet, the monitoring of firewood availability and usage have become very weak.

Aim: This study aimed to analyze the relationship between forest firewood availability and usage at the local scale.

Location: Tajikistan, Gorno Badakhshan, Ishkashim district.

Spatial and temporal scales: five case studies; annual average data.

Methods and data: The research framework of this study is adapted from Serna-Chavez et al., (2014) for illustrating the flow of forest firewood availability and usage. Forest biomass Mean Annual Increment (MAI) values were derived from literature (Novikov and Safarov, 2002; Kirchhoff, 2009), and two scenarios were used in the analysis. Forest firewood consumption data were derived from Mislimshoeva et al. (2014) for the case study areas. The budget between forest firewood availability and usage was bootstrapped (Efron and Tibshirani, 1993; Field et al., 2012) in order to estimate the standard error of the estimations.

Results: The main result of this paper showed that the budget between forest firewood availability and usage in most of the case studies turned out to be positive, which leads to the conclusion that unsustainable forest use may not occur in the research area. This, however, needs to be interpreted with caution for two major reasons: a) data on illegal forest firewood extraction and livestock pressure on forests are missing in the analysis; b) the households' firewood usage data used for this study contains some uncertainties (discussed chapter 9).

Main conclusions: There was high variability of woody biomass increment among forest plots and the firewood consumption among villages. Forest firewood supply and demand seems to be balanced in most of the case study areas, which needs to be interpreted with caution (e.g. for forest management decision making) due to reasons mentioned above.

6.3 Paper 3

Woody biomass estimation in semi-arid high mountainous region using high-resolution red edge and texture satellite features

Background: Remote sensing based biomass quantification in sparsely vegetated semi-arid to arid regions is often limited when relying only on conventional vegetation indices (VIs) such as the NDVI. Given the availability of high-resolution satellite data in combination with multi- or hyperspectral information, different techniques and sensors have been tested to tackle this issue. When synthesizing suggestions, the use of red edge band and texture attributes retrieved from high-resolution satellite data is often mentioned as improvement in this context. However, clear recommendations on the suitability of specific sensors and indices for woody biomass estimation in drylands is still lacking.

Aim: The main objective of this study is to improve the understanding of the interrelationship between multispectral high-resolution satellite data and ground-measured woody biomass information in semi-arid ecosystems.

Location: Tajikistan, Gorno Badakhshan, Ishkashim district.

Spatial and temporal scales: seven forest plots, 2013.

Methods and data: The methodological approach comprised three steps including: (1) Non-destructive ground-measured woody biomass information from 95 sampling transects distributed over seven forest plots was obtained to derive woody biomass volume of individual trees and shrubs; (2) high-resolution RapidEye satellite images covering the research area were processed and various indices with a special focus on red edge indices and texture measures were calculated; (3) ground and satellite based data sources were linked to find a correlation and woody biomass volume was spatially predicted for sampled forest stands. LASSO and Random forest were used as predictive model, and their performance was estimated based on spatial cross-validation, Pearson and Spearman's correlations and Root Mean Square Error (RMSE).

Results: The general predictive performance of the biomass model was rather low. The best model showed some predictive skills with correlations of 0.51, for LASSO, and 0.50, for RF, between measured values and predictions on cross-validated test sets at the logarithmic scales. Nonetheless, it was demonstrated that red edge indices and texture attributes improve the model results for woody biomass estimation in the semi-arid research region in comparison to focusing only on conventional broadband VIs.

Main conclusions: The research further improved the understanding of estimating woody biomass in semi-arid to arid environments using red edge and texture attributes retrieved from high-resolution satellite data. Still, as the achieved model performance highlights, biomass mapping in these environments is subject to substantial uncertainties. As main outlook, it is suggested to focus stronger on hyperspectral data to achieve better performances.

6.4 Paper 4

Current pathways towards good forest governance for ecosystem services in the former Soviet republic Tajikistan

Background: Forest ecosystems play an important role in the life of 50 million indigenous people and around 1.5 billion people depend on these resources for their livelihood (FAO, 2010). Thus, the sustainable management of these resources is crucial, but at the same time a challenging task for stakeholders (Rishi, 2007). Innovative participatory approaches have evolved and the impact of governance on the state of the forests has become more evident. It is now broadly accepted that the state of forest ecosystems and the services they provide is largely dependent on the chosen governance (Ostrom, 1999; FAO, 2010). Good forest governance consequently leads to sustainable forest management. However, because 'good forest governance' has no internationally agreed definition, of the definition used in this study is: a network of institutions wherein the interaction of transparent legal frameworks, decentralized decision-making and implementation is assumed to lead to the enhancement of ES of forests over time. This definition has been conceptualized and applied in Tajikistan's context as a case study region. Due to the history until the 1990s, "the socialistic state was the only owner of all forests" (Mukhin and Kryvda, 1976, p. 7) in Tajikistan. Today, the forest sector of the country needs to cope with a slow transition to market oriented, decentralized and participatory forestry.

Aims: In the context of transition, this study aimed to gain a broader understanding of the current state of the forest sector in Tajikistan. This included the complexity of the institutional setting at different administrative levels and the key challenges to achieve good forest governance. Furthermore, the aim was to give policy-relevant recommendations in order to overcome the key challenges. Additionally, the importance of forest ecosystem services was analyzed and their potential contribution to the sector's development was underlined.

Location: Tajikistan

Spatial and temporal scales: national level, 2014

Methods and data: For achieving the objectives of this research, a research framework was developed in order to link the good governance framework with the ES concept. The aim to link these concepts is that state forests, and consequently the provided services, are dependent on the form of governance chosen and vice versa. For the application of the research framework, the forest sector of Tajikistan was selected as a case study. 20 in-depth interviews were conducted with different stakeholders to collect quantitative and qualitative data of the forest sector. The main parts of the interviews were based on the good forest governance principles (legal frameworks, decision-making and implementation enforcement) and the importance of selected ES (food, fuelwood, wood, medical plants, erosion prevention, pollination, habitats for species, aesthetic values, tourism).

Results: The forest sector of Tajikistan established a set of institutions as a first step towards good forest governance. As for good forest governance principles, the legal frameworks of the forest sector are confronted with conflicting and overlapping laws and weak tenure regulation. Decision-making remains to a large extent central and there is a lack of capacity to engage stakeholders. The implementation enforcement lacks information technology, management plans and adequate capacity by foresters to oversee their assigned areas. Furthermore, relatively low salaries at all levels and weak cooperation to promote good forest governance are further barriers to be overcome. While the impact of forest governance on ES remains unclear (due to the lack of data), the results show that provisioning services can potentially contribute to the financial development of the sector.

Main conclusions: it is important to highlight two key issues — one relating to methods, the other relating the relevance of the study results. The proposed good forest governance definition of this study which is then integrated into practice-oriented conceptual framework can provides a structure for empirical analysis across administrative scales. Given the post-Soviet background, not only in Tajikistan, good institutional network and setting seems to be a first step towards good forest governance. Yet, several challenges remain in establishing sound legal frameworks, decision-making transparency, and implementation enforcement. Most of the challenges of the current forest sector are finance-dependent. ES could potentially contribute to financial stability through establishing markets for forest provisioning services.

7. References

Acharya, K., P., 2005 The Challenges of Forestry Research in Developing Countries: The Case of Nepal http://www.fao.org/docrep/ARTICLE/WFC/XII/0092-C1.HTM#fn1 Last visited May 2, 2015.

ADB (Asian Development Bank), 2014. Tajikistan. http://www.adb.org/sites/default/files/publication/31241/ado2014-tajikistan.pdf Last visited April 14, 2015.

Agrawal, A., Chhatre, A., Hardin, R., 2008. Changing governance of the world's forests. *Science 320,* 1460–1462.

Akhmadov, Kh., 2005. Capacity Building in Sharing Forest and Market Information, Country statement: Tajikistan - Forest Resources Assessment for Sustainable Forest Management. Report. Prague

Akhmadov, Kh., 2008. Forest and forest products country profile: Tajikistan. Report. Geneva.

Aldea, J., Martínez-Peña, F., Romero, C., Diaz-Balteiro, L., 2014. Participatory Goal Programming in Forest Management: An Application Integrating Several Ecosystem Services. *Forests, 5(12)*, 3352–3371.

Amacher, G., Ollikainen, M., Uusivuori, J., 2014.Forests and ecosystem services: Outlines for new policy options. *Forest Policy and Economics 47*, 1–3.

Angelsen, A., Wunder, S., 2003. Exploring the forest-poverty link: Key, concepts, issues and research implications. Center for International Forestry Research (CIFOR).Occasional Paper, 40. Bogor.

Antle, J., M., Valdivia, R., O., 2006. Modelling the supply of ecosystem services from agriculture: a minimum-data approach. *Australian Journal of Agricultural and Resource Economics 50* 1-15.

Aranha, J., T., Viana, H., F., Rodrigues, R., 2008. Vegetation Classification and quantification by satellite image processing. A case study in North Portugal, in: Bioenergy: Challenges and Opportunities - International Conference and Exhibition on Bioenergy, 7pp.

Arnold, M., Köhlin, G., Persson, R., 2006. Woodfuels, livelihoods and policy interventions: changing perspectives. *World Development 34* 596–611.

Arnold, M., Persson, R., 2003.Reassessing the fuelwood situation in developing countries. *International Forestry Review 5(4)* 379-383. doi:10.1505/IFOR.5.4.379.22660

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Mahler, K., G., Schneider, S., Starrett, D., Walker, B., 2004. Are we consuming too much? *Journal of Economic Perspectives 18* 147–172.

Asia-plus, 2015. Kyrgyzstan hopes to solve the problem of electricity imports from Tajikistan. http://www.asiaplus.tj/en/news/kyrgyzstan-hopes-solve-problem-electricity-imports-tajikistan Last visited May 24, 2015.

Bennett, E., M., Peterson, G., D., Gordon, L., J., 2009. Understanding relationships among multiple ecosystem services. *Ecology letters 12* 1394–1404.

Bhatt B., P., Sachan M., S., 2004. Firewood consumption along an altitudinal gradient in mountain villages of India. *Biomass and Bioenergy 27(1)*69–75.

Bicheron, P., Huc, M., Henry, C., Bontemps, S., Partners, G., 2008. GLOBCOVER Products Description Manual. ESA GlobCover Project led by Medias France.

Boyd, J., Banzhaf, S., 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics 63:* 616-626.

Braat, L. C., de Groot, R., 2012. The ecosystem services agenda: bridging the worlds of natural science and economics, conservation and development, and public and private police. *Ecosystem Services 1,* 4–15.

Brandt, M., Verger, A., Diouf, A., A., Baret, F., Samimi, C., 2014. Local Vegetation Trends in the Sahel of Mali and Senegal Using Long Time Series FAPAR Satellite Products and Field Measurement (1982–2010). *Remote Sensing* 6, 2408-2434; doi: 10.3390/rs6032408.

Breckle, S., Wucherer, W., 2006. Vegetation of the Pamir (Tajikistan): Land use and desertification problems. In: Spehn E, Liberman M, Ko¨rner C, editors. Land Use Change and Mountain Biodiversity. Boca Raton, FL: Taylor & Francis, pp 225–237.

Breu, T., Hurni, H., 2003. The Tajiks Pamirs: challenges of sustainable development in an isolated mountain region. Centre for Development and Environment (CDE). Report. Berne.

Briner, S., C. Elkin, R., Huber, Grêt-Regamey, A., 2012. Assessing the impacts of economic and climate changes on land-use in mountain regions: a spatial dynamic modeling approach. *Agriculture, Ecosystems and Environment 149* 50-63.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. *Ecological Indicators 21,* 17–29. doi:10.1016/j.ecolind.2011.06.019

Cashore, B., 2009a. Key components of good forest governance in ASEAN. Part I: overarching principles and criteria. Exlibris 6 1–8.

Cashore, B., 2009b. Key components of good forest governance in ASEAN. Part II: institu- tional fit, policy substance, policy instruments, and evaluation. Exlibris 6 9–20.

Chee, Y., E., 2004. An ecological perspective on the valuation of ecosystem services. *Biological Conservation 120* 549–565.

Chee, Y.E., 2004. An ecological perspective on the valuation of ecosystem services. *Biological Conservation 120* 549–565.

Costanza, R., (Ed.), 1991. Ecological Economics: the Science and Management of Sustainability. Columbia University Press, New York.

Costanza, R., 2008. Ecosystem services: Multiple classification systems are needed. *Biological Conservation 141 (2)* 350-352.

Costanza, R., d'Arge, R., De Groot, R., S., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruel, J., Raskin, R., G., Sutton, P., Van den Belt, M., 1997. The value of the world's ecosystem service and natural capital. *Nature 387*, 253–260.

Costanza, R., Daly, H., 1992. Natural capital and sustainable development. Conservation Biology 6, 37–46.

Ronald, G., Cummings, R., Burt, O., 1969. The Economics of Production from Natural Resources. The American Economic Review, Vol. 59, No. 5 (Dec., 1969), pp. 985-990

Daily, G., (Ed.), 1997. Nature's services: societal dependence on natural ecosystems. Island Press, Washington, DC.

Daily, G., C., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P., R., Folke, C., Jansson, A., M., Jansson, B., O., Kautsky, N., Levin, S., Lubchenco, J., Mäler, K., G., Simpson, D., Starrett, D., Tilman, D., Walker, B., 2000. The value of nature and the nature of value. *Science 289* 395–396.

de Groot, R., S., 1992. Functions of Nature: Evaluation of Nature in Environmental Planning, Management and Decision Making. Wolters-Noordhoff, Groningen.

de Groot, R., Wilson, M., A., Boumans, R., M., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics 41* 393–408

Démurger, S., Fournier, M., 2011. Poverty and firewood consumption: A case study of rural households in northern China. *China Economic Review, 22(4)*, 512–523.

Diouf, A., Lambin, E., F., 2001. Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal. J. *Arid Environments 48* 129–148.

Drigo, R., Masera, O., R., Trossero, M., A., 2002. Woodfuel Integrated Supply/Demand Overview Mapping – WISDOM: a geographical representation of woodfuel priority areas. *Unasylva 53* 36-40

Droux, R., Hoeck, T., 2005. Energy for Gorno Badakhshan: hydropower and the cultivation of firewood. Analysis of the energy situation in the Tajik Pamirs and its consequences for land use and natural resource management. Faculty of Natural Sciences. Joint Diploma Thesis. Berne.

Dunkerley, J., Macauley, M., Naimuddin, M., Agarwal, P., C., 1990.Consumption of fuelwood and other household cooking fuels in Indian cities. *Energy Policy 18(1)* 92–99.

Egoh, B., B., Reyers, M., Rouget, D., M., Richardson, D., C., Le Maitre, A., S., van Jaarsveld, 2008. Mapping ecosystem services for planning and management. *Agriculture, Ecosystems and Environment 127* 135-140. http://dx.doi. org/10.1016/j.agee.2008.03.013.

Ehrlich, P., R., Ehrlich, A., H., Holdren, J., P., 1977. Ecoscience: Population, Resources, Environment. W. H. Freeman, San Francisco.

Efron, B, Tibshirani, B., J., 1993. In introduction to the Bootstrap. CHAPMAN and HALL/CRC, USA

FAO (Food and Agriculture Organization), 2010. Emerging opportunities and challenges in forest finance and forest governance. http://www.fao.org/docrep/meeting/019/k8760e.pdf Last visited April 30, 2015.

FAO and ITTO (Food and Agriculture Organization and International Tropical Timber Organization), 2009.Forest governance and climate-change mitigation. http://www.fao.org/forestry/19488-0a2b1be34bcc2f24f780036ed0c5f9d69.pdf Last visited May 14, 2015.

Ferng, J., J., 2007. Human freshwater demand for economic activity and ecosystems in Taiwan. *Environmental Management 40(6)* 913–25.doi:10.1007/s00267-007-9023-0

Ferraro, P., J., Lawlor, K., Mullan, K., L., Pattanayak, S., K., 2011. Forest Figures: Ecosystem Services Valuation and Policy Evaluation in Developing Countries. *Review of Environmental Economics and Policy, 6(1)* 20–44.

Field, A., Miles, J., Field, Z., 2012. Discovering statistics using R. SAGE publication LtD, London, UK.

Fisher, B., Turner, R., K., 2008. Ecosystem services: classification for valuation. *Biological Conservation 141* 1167–1169.

Fisher, B., Turner, R., K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. *Ecological Economics 68* 643-653.

FLEGT (Forest Law Enforcement, Governance and Trade), 2015. What is FLEGT? http://www.euflegt.efi.int/home/ Last visited May 14, 2015.

Forest Code of Tajikistan, 2.08.2011.ЛеснойкодексРеспубликиТаджикистан. Dushanbe (in Russian).

Friedman, J., Hastie, T., Tibshirani, R., 2010.Regularization paths for generalized linear models via coordinate descent. *Journal of Statistical Software 33(1)* 1–22.

Friedman, J., Hastie, T., Tibshirani, R., 2012.Glmnet: Lasso and elastic-net regularized generalized linear models. Boston, MA: Free Software Foundation, Inc. R package version 1.9-3. http://cran.r-project.org/web/packages/glmnet; accessed on 27 May 2013.

GFI (The Governance of Forests Initiative), 2009. The governance of forests toolkit (version 1): a draft framework of indicators for assessing governance of the forest sector. The Governance of Forests Initiative http://pdf.wri.org/working_papers/gfi_tenure_indicators_sep09.pdf Last visited May 4, 2015.

Ghilardi, A., Guerrero, G., Masera, O., 2009. A GIS-Based Methodology for Highlighting Fuelwood Supply/Demand Imbalances at the Local Level: A Case Study for Central Mexico. *Biomass and Energy 33* 957–972.

Godfray, H., C., Crute, I., R., Haddad, L, Lawrence, D., Muir, J., F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C., Whiteley, R., 2010. The future of the global food system. *Philosophical Transactions of Royal Society B 365* 2769–2777.

Gómez-Baggethun, E., Ruiz-Pérez, M., 2011.Economic valuation and the commodification of ecosystem services. *Progress in Physical Geography 35(5)* 613–628.

Grêt-Regamey, A., Brunner, H., Kienast, F., 2012. Mountain Ecosystem Services: Who Cares? *Mountain Research and Development, 32(S1)* S23-S34.

Harrington, R., Anton, C., Dawson, T., P., De Bello, F., Feld, C., K., Haslett, J., R., Kluvánkova-Oravská, T., Kontogianni, A., Lavorel, S., Luck, G., W., Rounsevell, M., D., A, Samways, M., J., Settele,J., Skourtos, M., Spangenberg, J., A., Vandewalle, M., Zobel,M., Harrison, P., A., 2010. Ecosystemservices and biodiversity conservation: concepts and a glossary. *Biodiversity Conservation 19* 2773–2790.

Helliwell, D., R., 1969. Valuation of wildlife resources. *Regional Studies 3* 41–49.

Herbers, H., 2001. Transformation in the Tajik Pamirs: Gornyi-Badakhshan-an example of successful restructuring? *Central Asian Survey 20(3)* 367-381.

Hoeck, T., Droux, R., Breu, T., Hurni, H., Maselli, D., 2007. Rural energy consumption and land degradation in a post-Soviet setting – an example from the west Pamir mountains in Tajikistan. Centre for Development and Environment (CDE) 9, 1.

Holm, A., M., Cridland, S., W., Roderick, M., L., 2003.The use of time-integrated NOAA NDVI data and rainfall to assess landscape degradation in the arid shrubland of Western Australia.*Remote Sensing of Environment 85* 145–158.

Imhoff, M., L, Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., Lawrence, W., T., 2004. Global patterns in human consumption of net primary production. *Nature 429* 870–873.

IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services), 2012.About IPBES. http://www.ipbes.net/about-ipbes.html Last visited April 20, 2015.

Iskandarov, B., 2008. Значениеслова "Горно – Бадахшанская автономная область" в Большой Советской Энциклопедии, http://bse.sci-lib.com/article011836.htmlLastvisitedApril 5, 2015.

Jansson, A., M., Hammer, M., Folke, C., Costanza, R., (Eds.), 1994. Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Island Press, Washington, D.C.

Johnson, N., G., Bryden, K., M., 2012.Factors affecting fuelwood consumption in household cook stoves in an isolated rural West African village. *Energy 46(1)* 310–321.

Jujnovsky, J., González-Martínez, T., M., Cantoral-Uriza, E., A., Almeida-Leñero, L., 2012.Assessment of water supply as an ecosystem service in a rural-urban watershed in southwestern Mexico City.*Environmental Management 49(3)* 690–702. doi:10.1007/s00267-011-9804-3

Kassam, K.-A.S., 2009. Viewing Change Through the Prism of Indigenous Human Ecology: Findings from the Afghan and Tajik Pamirs. Human Ecology.DOI 10.1007/s10745-009-9284-8.

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, S., 2005.Quantifying grazing intensities using geographic information systems and satellite remote sensing in the Xilingol steppe region, Inner Mongolia, China. *Agriculture, Ecosystem and Environment 107* 83–93.

Kennes, W, Parikht, J., K, Stolwijk, H., 1984. Energy from biomass by socio-economic groups—a case study of Bangladesh. *Biomass 4* 209–234.

Kersten, I., Baumbach, G., Oluwole, A.F., Obioh, I., B., Ogunsola, O., J., 1998. Urban and rural fuelwood situation in the tropical rain-forest area of South-West Nigeria. *Energy 23,* 887–898.

Kirchhoff, J., F., Fabian, A., 2010.Forestry sector analysis. Report. Dushanbe.

Kishor, N., Rosenbaum, K., 2012. Assessing and Monitoring Forest Governance, A Users' Guide to a Diagnostic Tool. The Program on Forests (PROFOR), Washington DC http://www.profor.info/sites/profor.info/files/docs/AssessingMonitoringForestGovernance-guide.pdf Last visited April 14, 2015.

Kline, J., 2007. Designing an economics research program to describe and evaluate ecosystem services. Gen. Tech. Rep. PNW-GTR-700. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Koellner, T., 2009. Supply and demand for ecosystem services in mountainous regions. In: Alpine Space Man & Environment. Global Change and Sustainable Development in Mountain Regions, vol. 7.

Koellner, T., 2009. Supply and demand for ecosystem services in mountainous regions, in: Jandl, R.A., Borsdorf, H. Van Miegroet, R., Lackner, Psenner, R. (eds). Global Change and Sustainable Development in Mountain Regions. Innsbruck university press: Innsbruck. 61-70.

Kraus, T., Samimi, C., 2002.Biomass Estimation for Land Use Management and Fire Management using Landsat-TM and -ETM+. Erdkunde 56, 130–143.

Krutilla, J., V., 1967. Conservation considered, *American Economic Review, 57 (4)* 777-786.

Lazdinis, M., Carver, A., Lazdinis, I., Paulikas, V., 2009. From union to union: forest governance in a post-soviet political system. *Environmental Science and Policy, 12(3)*, 309–320.

Liu, S., Costanza, R., Farber, S., Troy, A., 2010.Valuing ecosystem services: Theory, practice, and the need for a transdisciplinary synthesis. *Annals of the New York Academy of Sciences 1185* 54–78.

MA (Millennium Ecosystem Assessment), 2003. Ecosystems and human well-being: a framework for assessment. Millennium ecosystem assessment. Island Press, Washington, DC.

MA (Millennium Ecosystem Assessment), 2005a. Ecosystems and Human Well-being. Synthesis. Island Press, Washington, DC.

MA (Millennium Ecosystem Assessment), 2005b. Current State and Trends Assessment. Island Press, Washington, DC.

Mahapatra, A., K., Mitchell, C., P., 1999. Biofuel consumption, deforestation, and farm level tree growing in rural India. *Biomass and Bioenergy 17(4)* 291–303.

Masera, O., Ghilardi, A., Drigo, R., Angel, M., 2006. WISDOM : A GIS-based supply demand mapping tool for woodfuel management. *Biomass and Bioenergy 30* 618-637. doi:10.1016/j.biombioe.2006.01.006

Mcdonald, R., 2009. Ecosystem service demand and supply along the urban-to-rural gradient. *Journal of Conservation Planning 5* 1–14.

MCFPE (Ministerial Conference on the Protection of Forest in Europe), 2015. What is Forest Europe? www.foresteurope.org Last visited May 8, 2015.

Meadows, D., H., Meadows, D., L., Randers, J., Behrens, W., W., 1972. The Limits to Growth. Potomac Associates. New York.

Miehe, G., Winiger, M., Böhner, J., Yili, Z., 2001. The climatic diagram map of High Asia. Purpose and concepts. *Erdkunde 55* 94–97.

Mislimshoeva, B., Samimi, C., Kirchhoff, J., F., Koellner, T., 2013. Analysis of costs and people's willingness to enroll in forest rehabilitation in Gorno Badakhshan, Tajikistan. *Forest Policy and Economics 37* 75–83.

Muhabbatov, M., Khonaliev, N., 2005. Памир, ресурсный потенциал и перспективы развития экономики. Master Print. Dushanbe.

Mukhin, I., Kryvda, A., 1976. Леса колхозов и совхозов и ведение хозяйства в них (Forests collective and state farms and farming them). Лесная промышленность (Forest industry), Moscow (in Russian).

Nadrowski, K., Wirth, C., Scherer-Lorenzen., M., 2010. Is forest diversity driving ecosystem function and service? *Current Opinion on Environmental Sustainability* 2, 75–79.

Nedkov, S., Burkhard, B., 2011.Flood regulating ecosystem services - Mapping supply and demand, in the Etropole municipality, Bulgaria. *Ecological Indicators in press.* doi:10.1016/j.ecolind.2011.06.022

Nijozmamadov, A., 2005. История Горно-Бадахшанской автономной области. Second ed. Dushanbe.

Norgaard, R., B., 2010. Ecosystem services: from eye-opening metaphor to complexity blinder. *Ecological Economics 69* 1219–1227.

Novikov, V., Safarov, N., 2003. State of the Environment in Tajikistan. http://enrin.grida.no/htmls/tadjik/soe2001/eng/htmls/forest/state.htm Last visited March 22, 2015

Okello, B., D., O'Connor, T., G., Young, T., P., 2001. Growth, biomass estimates, and charcoal production of Acacia drepano- lobium in Laikipia, Kenya. *Forest Ecology and Management 142* 143–153.

Onoja, A., O., 2012. Econometric analysis of factors influencing fuel wood demand in rural and peri-urban farm households of Kogi State. *Sustainable Development 8* 115–127.

Ostrom, E., 1999. Self-Governance and Forest Resources. CIFOR occasional paper. 62(20). ISSN08549818

Paetzold, A., Warren, P., H., Maltby, L., L., 2010. A framework for assessing ecological quality based on ecosystem services. *Ecological Complexity 7* 273–281.

Parikka, M., 2004.Global biomass fuel resources. *Biomass and Bioenergy, 27(6)* 613–620. doi:10.1016/j.biombioe.2003.07.005

Patterson, T., Coelho, D., 2009. Ecosystem services: Foundations, opportunities, and challenges for the forest products sector. *Forest Ecology and Management 257* 1637–1646.

Pearce, D., Moran, D., 1994. The economic value of biodiversity. Earthscan Publications, London.

Prugh, T., Costanza, R., Cumberland, J., H., Daly, E., Goodland, R., Norgaard, B., 1999. Natural Capital and Human Economic Survival. Lewis Publishers, Boca Raton, Florida.

Qi, J., Wallace, O., 2002. Biophysical Attributes Estimation from Satellite Images in Arid Regions. IEEE Trans. Geoscience and Remote Sensing Symposium. IEEE International, Volume: 4, IEEE Xplore.

Rametsteiner, E., 2009. Governance concepts and their application in forest policy initiatives from global to local levels. *Small Scale Forestry 8* 143–158.

Randall, A., Castle, E., 1985. Land resources and land markets. In Handbook of Natural Resource and Energy Economics, vol. II, ed. Kneese, A., V., Sweeney, J., L. Elsevier Science Publishers B. V.

Raudsepp-Hearne, C., Peterson, G., D., Bennett, E., M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *PNAS 107* 5242–5247.

Rehnus, M., Nazarek, A., Mamadzhanov, D., Venglovsky, B., I., Sorg, J., P., 2013. High demand for firewood leads to overuse of walnut-fruit forests in Kyrgyzstan. *Journal of Forestry Research 24(4)* 797–800.

Rishi, P., 2007. Joint forest management in India: An attitudinal analysis of stakeholders. *Resources, Conservation and Recycling, 51(2)* 345–354. doi:10.1016/j.resconrec.2006.10.009

Romer, D., 2005.Agroforestry in Tajikistan. Report, Dushanbe.

Rounsevell, M., D., A., Dawson, T., P., Harrison, P., A., 2010. A conceptual framework to assess the effects of environmental change on ecosystem services. *Biodiversity and Conservation 19* 2823–2842.

Sagoff, M., 2008.On the economic value of ecosystem services. *Environnemental Values 17* 239-257.

Samant, S., Dhar, U., Rawal, R., 2000.Assessment of fuel resource diversity and utilization patterns in Askot Wildlife Sanctuary in Kumaun Himalaya, India, for conservation and management. *Environmental Conservation 27(1)* 5–13.

Samimi, C., 2003. Das Weidepotential im Gutu Distrikt Möglichkeiten und Grenzen der Modellierung unter Verwendung von Landsat TM-5. Karlsruher Schriften zur Geographie und Geoökologie, Band 19, 137pp.

Samimi, C., Kraus, T., 2004.Biomass estimation using Landsat-TM and -ETM + Towards a regional model for Southern Africa? *GeoJournal 59,* 177–187.

San, V., Spoann, V., Ly D., Chheng, N., V., 2012. Fuelwood consumption patterns in Chumriey Mountain, Kampong Chhnang Province, Cambodia. *Energy 44(1)* 335–346.

Schröter, M., van der Zanden, E., H., van Oudenhoven, A., P., E., Remme, R., P., Serna-Chavez, H., M., de Groot, R., S., Opdam, P., 2014. Ecosystem services as a contested concept: a synthesis of critique and counter-arguments. Conserv. Lett. http://dx.doi.org/10.1111/ conl.12091.

Secco, L., Da Re R., Matteo Pettenella, D., Gatto P., 2013. Why and how to measure forest governance at local level: A set of indicators. *Forest Policy and Economics 49* 57–71.

SEEDS (Social Enterprise and Environmental Development Systems). 2008. Bio-Mass Energy Use in GBAO. Khorog, Tajikistan: Social Enterprise & Environmental Development Systems.

Sharma, C., M., Gairola, S., Ghildiyal, S., K., Suyal, S., 2009. Forest resource use patterns in relation to socioeconomic status. *Mountain Research and Development 29(4)* 308–319.

Singh, G., Rawat, G., S., Verma, D., 2010. Comparative study of fuelwood consumption by villagers and seasonal ''Dhaba owners'' in the tourist affected regions of Garhwal Himalaya, India. *Energy Policy 38(4)* 1895–1899.

Song, N., Aguilar, F., X., Shifley, S., R., Goerndt, M., E., 2012. Factors affecting wood energy consumption by U.S. households. *Energy Economics 34(2)* 389–397.

TEEB, 2010. The Economics of Ecosystems and Biodiversity. Mainstreaming the Economics of Nature: a synthesis of the approach, conclusions and recommendations of TEEB.

The World Bank, 2009. Republic of Tajikistan. Poverty Assessment. Report No. 51341-TJ. Dushanbe. https://openknowledge.worldbank.org/bitstream/handle/10986/3159/513410ESW0P112101Official0Use0Only1.pdf?sequence=1 Last visited April 14, 2015.

The World Bank, 2014a. Rural population in Tajikistan. http://www.tradingeconomics.com/tajikistan/rural-population-percent-of-total-population-wb-data.html Last visited April 10, 2015.

The World Bank, 2014b. Tajikistan. http://data.worldbank.org/country/tajikistan Last visited April 17, 2015.

The World Bank, 2014c. Assessment of household energy deprivation in Tajikistan. Policy options for social responsible reform in the energy sector. Report. Tajikistan

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W., H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. *Science 292* 8–10.

Top, N., Mizoue, N., Ito, S., Kai, S., 2004.Spatial analysis of woodfuel supply and demand in Kampong Thom Province, Cambodia. *Forest Ecology and Management 194(1-3)* 369–378. doi:10.1016/j.foreco.2004.02.028

Tucker, C., M., 2010. Learning on Governance in Forest Ecosystems : Lessons from Recent Research. *International Journal 4(2)* 687–706.

UN (United Nations), 2012. World Population Prospects: The 2012 Revision. http://esa.un.org/wpp/Excel-Data/population.htm Last visited April 3, 2015

UN (United Nations), 2014. The Value of Forests.Payments for Ecosystem Services in a Green Economy. Study paper 34. e-ISBN 978-92-1-056451-9

UN (United Nations), 2013. World population. Press release. http://esa.un.org/wpp/Documentation/pdf/WPP2012_Press_Release.pdf Last visited April 3, 2015

UNDP (United Nations Development Programme), 2008. Tajikistan. http://www.undp.tj/index.php?option=com_content&task=view&id=112&Itemid=162 Last visited March 9, 2015.

Vanselow, K., 2011. The high-mountain pastures of the Eastern Pamirs (Tajikistan). An evaluation of the ecological basis and the pasture potential. PhD thesis. Erlangen.

Vemuri, A., 2008. Joint Forest Management in India: An Unavoidable and Conflicting Common Property Regime in Natural Resource Management. *Journal of Development and Social Transformation 5* 81–90.

WB-ARD, 2009. Roots for good forest Outcomes: an analytical framework for governance reforms. Report no. 49572-GLB. The World Bank, Agriculture and Rural Development Department, Washington, DC.

Wessels, K., J., Prince, S., D., Zambatis, N., MacFadyen, S., Frost, P., E., Van Zyl, D., 2006. Relationship between herbaceous biomass and 1-km 2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa.*International Journal of Remote Sensing 27* 951–973.

WRI (World Resources Institute), 2013. Assessing Forest Governance. The Governance of Forests Initiative Indicator Framework. http://www.wri.org/sites/default/files/assessing_forest_governance.pdf Last visited May 10, 2015.

Xu, B., Yang, X., C., Tao, W., G., Miao, J., M., Yang, Z., Liu, H., Q., Jin, Y., X., Zhu, X., H., Qin, Z., H., Lv, H., Y., Li, J., Y., 2013. MODIS-based remote-sensing monitoring of the spatiotemporal patterns of China's grassland vegetation growth. *International Journal of Remote Sensing 34* 3867–3878.

Zhen, L., Liu, X., L., Wie, Y., J., Yang, L., Long., X., Du, B., Li, F., Cao, X., 2011. Consumption of ecosystem services: A conceptual framework and case study in Jinghe watershed. *Resources and Ecology 2* 298–306.

Zibung, D., 2003. An economy in transition. In Breu, T., Hurni, H., 2003. The Tajiks Pamirs: challenges of sustainable development in an isolated mountain region. Centre for Development and Environment (CDE). Report. Bern.

PART II

PUBLICATIONS

8.

Factors influencing households' firewood consumption in the Western Pamirs, Tajikistan

Bunafsha Mislimshoeva*[1], Robert Hable[2], Cyrus Samimi[3], Abdulnazar Abdulnazarov[4], Manuchehr Fezakov[5], Thomas Koellner[1]

Published in

Mountain Research and Development 34:2. p. 147–156

Peer-reviewed: March 2014. Accepted: April 2014

*Corresponding author: bunafsha.mislimshoeva@uni-bayreuth.de

[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[2]Chair of Stochastics, Department of Mathematics, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[3] Regional Program on Sustainable Use of Natural Resources in Central Asia, Deutsche Gesellschaft für Internationale Zusammenarbeit, Erkindik Blvd 22, Bishkek 720040, Kyrgyz Republic

[4] Professorship of Climatology, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[5] State Forest Agency of Gorno Badakhshan Autonomous Oblast, Kadamshoev Street 96/4, 736000 Khorog, Tajikistan

BioOne RESEARCH EVOLVED

Factors Influencing Households' Firewood Consumption in the Western Pamirs, Tajikistan

Author(s): Bunafsha Mislimshoeva, Robert Hable, Manuchehr Fezakov, Cyrus Samimi, Abdulnazar Abdulnazarov, and Thomas Koellner

Source: Mountain Research and Development, 34(2):147-156. 2014.
Published By: International Mountain Society
DOI: http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00113.1
URL: http://www.bioone.org/doi/full/10.1659/MRD-JOURNAL-D-13-00113.1

BioOne (www.bioone.org) is a nonprofit, online aggregation of core research in the biological, ecological, and environmental sciences. BioOne provides a sustainable online platform for over 170 journals and books published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Web site, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/page/terms_of_use.

Usage of BioOne content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

MountainResearch
Systems knowledge

Factors Influencing Households' Firewood Consumption in the Western Pamirs, Tajikistan

Bunafsha Mislimshoeva[1]*, Robert Hable[2], Manuchehr Fezakov[3], Cyrus Samimi[4], Abdulnazar Abdulnazarov[5], and Thomas Koellner[1]

** Corresponding author: bunafsha.mislimshoeva@uni-bayreuth.de*

[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[2] Chair of Stochastics, Department of Mathematics, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[3] Regional Program on Sustainable Use of Natural Resources in Central Asia, Deutsche Gesellschaft für Internationale Zusammenarbeit, Erkindik Blvd 22, Bishkek 720040, Kyrgyz Republic

[4] Professorship of Climatology, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[5] State Forest Agency of Gorno Badakhshan Autonomous Oblast, Kadamshoev Street 96/4, 736000 Khorog, Tajikistan

Open access article: please credit the authors and the full source.

Firewood is a major energy source, especially in many high mountainous regions in developing countries where other energy sources are limited. In the mountainous regions of Tajikistan, current energy consumption is limited owing to geographic isolation and numerous challenges—including in the energy sector—that emerged after the collapse of the Soviet Union and Tajikistan's independence. The sudden disruption of external supplies of energy forced people to rely on locally available but scarce biomass resources, such as firewood and animal dung. We conducted an empirical study to gain an understanding of current household energy consumption in the Western Pamirs of Tajikistan and the factors that influence firewood consumption. For this purpose, we interviewed members of 170 households in 8 villages. We found that, on average, households consumed 355 kg of firewood, 253 kWh of electricity, 760 kg of dung, and 6 kg of coal per month in the winter of 2011–2012. Elevation, size of a household's private garden, and total hours of heating had a positive relationship with firewood consumption, and education level and access to a reliable supply of electricity showed a negative relationship.

Keywords: *Energy; firewood consumption; dung; mountainous regions; Tajikistan.*

Peer-reviewed: *March 2014* ***Accepted:*** *April 2014*

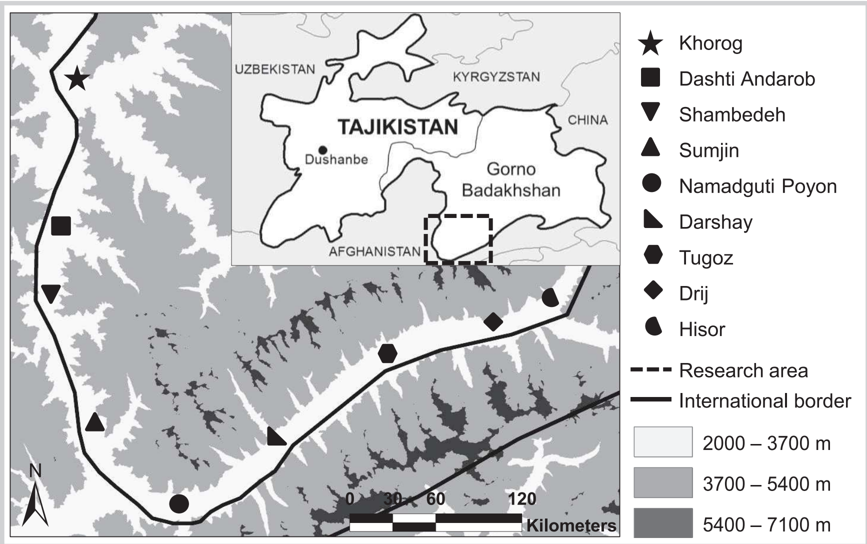
Introduction

In the past few decades, increasing consumption levels have led to more pressure on natural resources worldwide (Tilman et al 2001; Arrow et al 2004; Imhoff et al 2004; Godfray et al 2010; Liu et al 2010; Zhen et al 2011). The demand for energy is partly met by firewood, which is a primary energy source in many developing countries (Kennes et al 1984; Hosier and Kipondya 1993; Bhatt et al 1994; Tabuti et al 2003; Chen et al 2006; Khuman et al 2011; San et al 2012; Rehnus et al 2013). This is particularly critical in mountainous regions, where limited energy sources lead to high pressure on scarce natural resources.

In the mountainous areas of Gorno Badakhshan Autonomous Oblast in Tajikistan (also known as the Tajik Pamirs), the high demand for energy is believed to be one of the main reasons for natural resource degradation (Breu and Hurni 2003; Hoeck et al 2007; Kirchhoff 2010). Here, winter lasts up to 6 months, during which local people heat their homes all day because of very low temperatures. The unique history of Tajikistan during and after the Soviet era also shaped the current energy situation. During the Soviet period in Gorno Badakhshan, local homes and office buildings were supplied with a large quantity of highly subsidized fuel, including coal, kerosene, diesel, oil, and gas (Breu and Hurni 2003; Hoeck et al 2007; Mislimshoeva et al 2013). This external supply abruptly stopped after the Soviet Union dissolved and Tajikistan gained independence in 1991.

The transition away from a subsidized energy system has had massive consequences for the availability, quantity, and quality of energy. The current energy situation forces reliance on scarce locally available resources. In many villages, firewood and animal dung are the main source of energy for cooking and heating (Breu and Hurni 2003; Hoeck et al 2007). Energy scarcity also influences trade-offs between ecosystem services such as energy and food. For example, in Gorno Badakshan, the quality of agricultural products is reduced because the demand for dung for heating is high, leaving less available for farming.

FIGURE 1 Map of the study area with study site locations and elevations. (Map by first author; digital elevation model by NASA LP DAAC 2013; country border line by APRS 2013)



Despite the importance of firewood in the daily lives of people in the Western Pamirs, very few empirical studies of firewood consumption exist (see Hoeck et al 2007), and official data on forests and other woody vegetation are lacking. Furthermore, no attempts have been made to quantify the association between firewood consumption and factors that influence it. This empirical study was carried out to gain an understanding of the extent and patterns of household consumption of firewood and other sources of energy in the Ishkashim District in the Western Pamirs and the factors influencing it. This understanding is crucial for sustainable management of energy sources not only in the Western Pamirs but also in other regions of the world with similar historical background or biophysical conditions.

Methodology

Research area

The Western Pamirs are rocky, high mountains with an elevation range of 2200–7500 masl (Figure 1). The topography features fast-flowing glacier-fed rivers in deeply incised valleys. The high elevation has a direct impact on the climate of the region. The Western Pamirs are characterized by low temperatures, lack of large surface water bodies, dry air, and moderate diversity of microclimatic conditions. High mountain ranges in the north and south form a natural barrier against the flow of moist air, thus creating a continental climate. Maximum temperatures occur in July and are on average between 18 and 20°C. Minimum temperatures typically occur in January and are on average between −8 and −2°C. The average annual rainfall is 100–300 mm, mostly occurring from December to April (Miehe et al 2001; Breckle and Wucherer 2006).

The district of Ishkashim was selected as the study site (Figure 1). According to data obtained from the district administration, about 25,000 people live in the district, dispersed among 47 villages. The number of households per village ranges from 15 to 260. Farming and livestock breeding are the main sources of livelihood; some households are also involved in forestry. In total, district residents own about 12,000 large and 47,000 small livestock animals. Total surface area of the district is 350,000 ha, including around 21,000 ha of agricultural land (arable and rainfed lands, where summer crops are cultivated) and 11,000 ha of pastures for livestock grazing. Roughly 2300 ha are designated as forest; of this, only about 1800 ha are actually covered by forest. The other 500 ha are currently bare soil; a few decades ago, this was also a forested area. The total area of gardens (a piece of private land owned by a household, where trees and hay are grown) in the district is 290 ha (IDA 2013; SFA 2013). Although total garden area is small, each household maintains a private garden in which hay, fruit and nonfruit trees, and vegetables are grown.

Firewood and dung are the main heating fuels. Firewood is extracted from private gardens; gorges and roadsides; and state, community, and private forests. Almost all households have livestock and thus have dung available. Our 2013 field observations showed that trade-offs are taking place between firewood and dung provision. As there is not enough precipitation, many forest plots are additionally irrigated, and there is not always enough water to irrigate both forests and agricultural land. As agricultural products are required for daily life, people give priority to irrigating agricultural land. In the case of dung, the trade-off is between its use as fuel and fertilizer. In that case, local people give priority to its use as fuel; the resulting lack of fertilizer potentially reduces crop yield and quality.

TABLE 1 Case study villages and sample sizes.

Village	Location	Households in village	Households surveyed	Surveyed households as % of total households
Darshay	36°79′N, 71°99′E	58	23	40
Dasht	37°22′N, 71°48′E	41	16	40
Drij	37°00′N, 72°49′E	58	23	40
Hisor	36°03′N, 72°65′E	98	32	33
Namadguti Poyon	36°67′N, 72°74′E	41	16	40
Shambedeh	36°09′N, 71°45′E	56	21	38
Sumjin	36°83′N, 71°55′E	41	16	40
Tugoz	37°00′N, 72°49′E	57	23	40
Total		450	170	38

In some villages, especially those closer to Khorog (the capital of Gorno Badakhshan), energy demand for cooking is partly met by electricity. A very small amount of coal reaches the more remote villages but is often expensive and of poor quality.

Site selection, data collection, and analysis

The fieldwork was carried out in February and March 2013 to coincide with the heating season and observe the use of different energy sources. Before selecting the study villages, semistructured interviews were conducted with the official heads of all 7 *jamoats* (subdistricts) in Ishkashim District. The *jamoats* have an average of 6 villages each. During the interviews, information was collected on the number of inhabitants, number of households, migration rate, livestock numbers, main source of energy in summer and winter, and duration of the heating season. Based on this information, 3 criteria were developed for selecting study villages:

1. Number of households in the village: Although this number ranges widely in Ishkashim District (from 14 to 365), medium-size villages were selected with a similar number of households to balance the total number of visited villages and the total number of interviews.
2. Energy use: Villages that used a variety of energy sources and types were selected.
3. Duration of heating season: Villages with different heating season lengths (from 4 to 6 months, depending on the elevation) were chosen, again to ensure variety.

In total, 8 case study villages were selected in the 7 *jamoats*. Next, a list of households was obtained from the village leader in each village. Nearly 40% of the total households in the village were selected for interviews using simple random sampling. Table 1 and Figure 1 give an overview of the villages and the number of interviews.

All interviews were based on a questionnaire administered at the household level; the questionnaire took approximately 35 minutes to complete and had 5 sections:

1. Demographic and socioeconomic characteristics: number of household members, age, education, occupation, and monthly income amount and source;
2. Property: size of the private garden, including private forest (a piece of forest that is owned by a household), size of agricultural land, number of small and large livestock, and source of fodder;
3. House and heating infrastructure: type and size of the room(s), type of stove, number of heating hours per day in winter, heating season duration, and availability of electricity;
4. Energy: types of energy used, sources, quantity, purpose, and price;
5. Firewood: sources, collection methods, and species.

Most families spend the winter in a single room to save heating costs. Houses have mainly two types of rooms: (1) a traditional Pamiri room with a large space, relatively high ceilings, two windows to the outside, and a skylight; and (2) a small room with low ceilings and usually one window to the outside. Almost all interviews were conducted in such rooms.

The interviewees were not necessarily the heads of the families but, rather, those who were usually responsible for lighting and maintaining the fire and cooking. Interviewees included men and women. During the interviews, the unit of measure was the one used locally: a bag. Interviewees were shown a bag of 50 × 100 cm, and they estimated the number of bags of firewood and dung used per day. These quantities was multiplied by 30 to get a monthly value. Electricity was measured in kilowatt hour (kWh), by dividing the average amount of money paid for electricity per month by the price for 1 kWh of electricity, which was TJS0.13 (US$0.6). Coal was measured in kilograms per month. Units were later converted to megajoules (MJ) for direct comparison of energy amounts, as shown below (Equations 1 to 4; conversion sources: Hoeck et al 2007; GIZ 2011; FAO 2013).

$$firewood[MJ] = \frac{x\ bags/day\ *30\ days}{16\ bags/m^3} * 150\ kg/m^3 * 15MJ/kg \tag{1}$$

$$dung[MJ] = x\ bags/day * 30\ days\ * 20kg/bag * 12MJ/kg \tag{2}$$

$$electricity[MJ] = x\ kWh * 3.6\ MJ/kWh \tag{3}$$

$$coal[MJ] = x\ kg * 28\ MJ/kg \tag{4}$$

The data were analyzed using the statistical software R (version 3.0.0; R Core Team 2014). Given the nature of interview data, a basic linear model was used, including only main effects and no interactions. As the data set consisted of 170 data points and 51 potentially influential variables, a variable selection had to be done in the linear regression. The variable selection was done using LASSO (R-package "glmnet," Friedman et al 2010; 2012), which is a straightforward method based on penalized regression. It is suitable for large numbers of potentially influential variables and not limited to any critical assumptions like the normal distribution (see Hastie et al 2009 for details). All variables that were noninfluential according to the LASSO estimate were removed, and the effect coefficients of the remaining variables were estimated by ordinary least-squares regression. The resulting regression model was validated by a 10-fold cross-validation, which also considered the prior variable selection.

Results

Demographic and socioeconomic features

The study villages contained 6 people per household on average. Several households had as many as 17 family members and some as few as 2 or 3. The following age categories were used in this study: younger than 3 years (babies), 3–6 years old (small children), 7–17 years old (schoolchildren), 18–25 years old (young adults), 26–40 years old (adults I), 41–55 years old (adults II), and older than 56 years (older adults). The greatest number of household members were in the 7–17 years old group, followed by the 26–40 years old group; the 18–25 years old group was much smaller than either of these (Table 2).

Three occupational categories were used: unemployed (children and other family members without a cash income), employed (state employees with low but regular wages, persons with small-scale enterprises with regular income, and self-employed people with seasonal income, and retired (pensioners with relatively low incomes; retirement age is 63 for men and 58 for women in Tajikistan) (Falkingham et al 2009).

Most (75%) of the household members were in the unemployed category (children were included in this group as they did not have any income that could influence firewood consumption). Of the remainder, 10% were retired and 15% were employed.

Education levels were categorized as follows: school level (9–11 years of education at a primary and secondary school), education level I (3–4 years of vocational and technical education), and education level II (>5 years of higher university education). For the statistical analysis, the family member who completed the highest education level was chosen. It was assumed that education might influence energy consumption level, for example, through use of energy-efficient technology. Of the 170 households, 55% had at least one member with a level I education, 25% had a member with a level II education, and 20% had a member with school-level education.

Monthly household cash income included salaries, remittances from family members working in Russia, and income from trade. For this study household cash income was categorized as low (less than TJS200 or US$42), medium (TJS201–500 or US$42–104), or high (more than TJS501 or US$104). Most households (54%) were in the middle-income category; the rest were almost evenly divided between the high and low categories. Income in the study area is relatively low. Per capita per month income is around TJS100 (US$20), which is below the national poverty line of TJS139 (US$42) per capita per month (World Bank 2009).

Energy consumption

Households use a combination of different energy sources. Out of these different sources, in all villages dung was the most commonly used, followed by firewood (Figure 2). Households used an average of 9095 MJ of energy from dung and 5329 MJ of energy from firewood per month during winter. Because of the low quality or irregular supply of electricity and the lack of coal, these 2 sources of energy were used the least. On average, households used 911 MJ electricity and 187 MJ coal. Average total annual energy consumption is 86 gigajoules (GJ) per household and 17 GJ per person. Energy consumption varies along the altitudinal gradient (Table 3). It also differs considerably depending on the heating and nonheating season (Table 4).

Dung and firewood were mainly used for heating and cooking, and electricity was mostly used for lighting and sometimes for cooking and boiling water. Heating devices in 97% of the interviewed households were the same—a typical, locally made stove with a bake-oven (Figure 3). Only 2 houses were insulated and had improved stoves for heating and cooking.

TABLE 2 Demographic and socioeconomic characteristics of the respondents.

Variable	Category	Number	%
(By person; N = 1012)			
Age (years)	<3	52	5
	3–6	97	10
	7–17	254	25
	18–25	99	10
	26–40	200	20
	41–55	176	17
	56 or older	134	13
Work status	Retired	104	10
	Unemployed	758	75
	Employed	150	15
By household (N = 170)			
Education level	School level (9–11 years)	35	20
	Education level I (3–4 years)	92	55
	Education level II (+ 5 years)	43	25
Monthly income[a]	Low (≤TJS200)	38	22
	Medium (TJS201–500)	92	54
	High (≥TJS501)	40	24
Source of income	Local	95	56
	Abroad	14	8
	Both	61	36

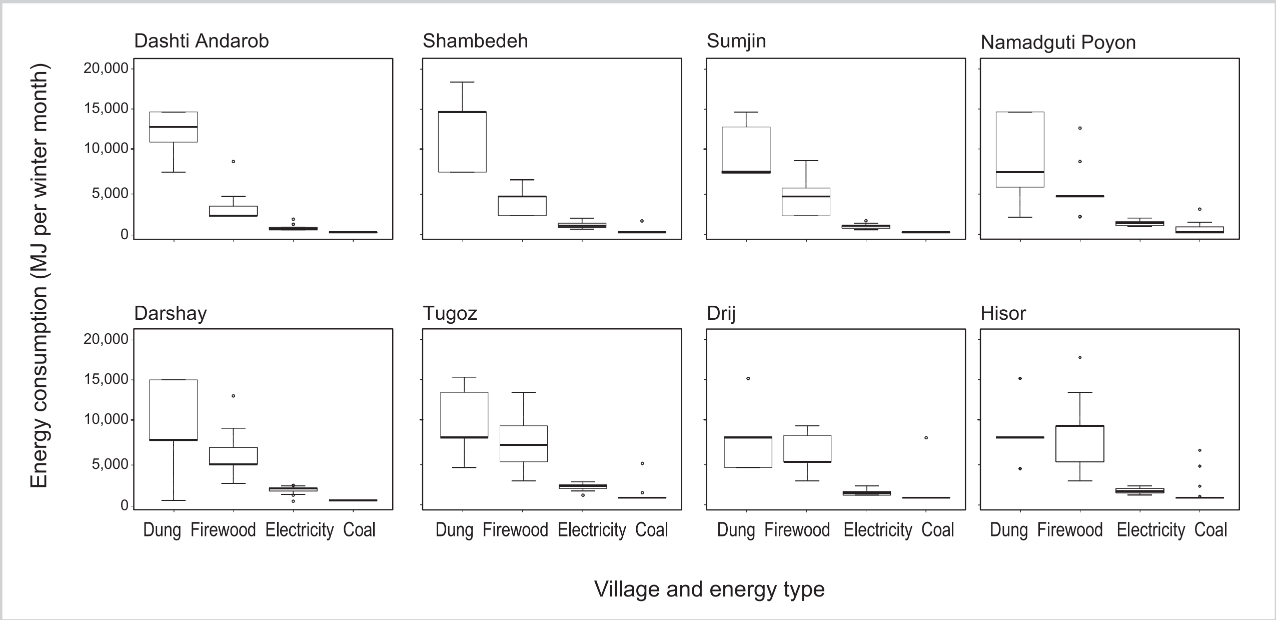
[a]US$1 = TJS4.8 (National Bank of Tajikistan 2013).

To save energy, all household members live in the same room during winter. Of the families participating in the study, 66% spent winter in a traditional Pamiri room, with an average size of 49 m^2. These were mostly households with more than 6 family members. The other 34% had a separate room with an average size of 24 m^2, in most cases specially built for winter but not necessarily insulated. Given the harsh winter conditions, every household heats the room during the day and typically prepares warm meals 3 times a day. Heating hours per month ranged from 120 to 480 with an average of 380.

Interview participants were also asked to rate their satisfaction with the availability of different energy sources (Table 5). Most were moderately or very satisfied with dung availability. Each household owned, on average, 11 small and 3 large livestock animals and thus had dung available. Households were only moderately satisfied with the availability of firewood, which was not as universally available. Satisfaction with electricity availability varied; those who were very satisfied were mostly those who received electricity from the city of Khorog, and this source was stronger and more reliable than the electricity supplied by a local plant. Very few participants were satisfied with the availability of coal.

The variety of firewood sources is summarized in Figure 4. The biggest share came from private gardens, which contained fruit trees and other woody vegetation used as firewood; the average size was around 830 m^2. Unlike firewood from other sources, this wood has no extra cost. The price of firewood is higher in villages where it must be transported from far away. Only 5 households relied completely on purchased firewood for the winter months, 93 households obtained their firewood at no cost, and 72 households bought firewood from different sources as well as extracting it from their private gardens. On average, households pay TJS29 (US$6) per month for firewood in winter. The cost of a cubic meter of firewood was around TJS50 (US$10).

FIGURE 2 Use of different energy sources in the studied villages.



The second most significant source of firewood was state forest land, used mostly by villagers living near a state forest. Local people either buy this firewood or harvest it according to the Joint Forest Management approach (see Mislimshoeva et al 2013 for details about this approach). The third most common source was the free firewood available in the mountains (mainly gorges), along roadsides, and around fields. This option was usually used by villages that have no forest area nearby, such as Shambedeh and Dashti Andarob.

Factors influencing firewood consumption

Firewood consumption in the villages is positively influenced by elevation, size of the household's private garden, and hours of heating in winter, and it is negatively influenced by level of education and electricity received from the city (Table 6; Figure 5). We found that elevation correlates positively with heating hours per month and firewood consumption, as winter tends to be colder and lasts longer at high elevations. Education tended to play a role in firewood consumption, and education level I correlated positively with lower firewood consumption. Firewood use also appeared to increase with the size of the garden. Households that received electricity from Khorog, on the other hand, used less firewood than those that did not.

Model validation

To estimate the prediction error, the widely used 10-fold cross-validation method was chosen (Oslon and Delen 2008; Fushiki 2009; Hastie et al 2009). During cross-validation, the estimation of the effect of the coefficients and the prior variable selection by LASSO were taken into consideration. The square root of the overall mean squared prediction error in the cross-validation was 2500 MJ. As the standard deviation for firewood consumption was about 3000 MJ, this showed that the model explains a considerable part of the firewood consumption patterns but that the variability of firewood consumption is rather high. One reason for this relatively high prediction error might be the fact that the amount of firewood consumption was only estimated by the interviewed households, and this incorporates an additional random error that cannot be predicted. The high variability can also be seen from the adjusted coefficient of determination (equal to 0.35) and the square root of the mean squared residuals (equal to 2300 MJ). However, the meaning of these values is limited,

TABLE 3 Average energy consumption per household by elevation/heating season.

Elevation (masl)	Heating season	Firewood (kg)	Dung (kg)	Coal (kg)	Electricity (kWh)
Low (2450)	4 months	1100	3700	19	980
Middle (2650)	5 months	1900	3900	17	1800
High (2800)	6 months	2700	3500	70	1200

52

http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00113.1

TABLE 4 Average energy consumption per household for all elevations.

Time frame	Firewood (kg)	Dung (kg)	Coal (kg)	Electricity (kWh)
Per month during heating season	355	760	6	253
Total heating season	1840	3700	35	1270
Total nonheating season	*	100	0	2300
Full year	1840	3800	35	3570

*Negligible amount (0.07 kg).

as they are not cross-validated and do not take into account the prior variable selection.

Discussion

Factors influencing firewood consumption

As energy consumption is very heterogeneous, it is challenging to directly compare these findings with those of other studies. Nevertheless, similar energy consumption patterns can be observed in other comparable regions (for example, see Samant et al 2000; Bhatt and Sachan 2004; Hoeck et al 2007; SEEDS 2008; Sharma et al 2009; Singh et al 2010; Démurger and Fournier 2011; Rehnus et al 2013).

Many studies have explored the different relationships between firewood consumption and such factors as income, family size, number of heated rooms, price of firewood, and climate (Kennes et al 1984; Dunkerley et al

FIGURE 3 (A) Dung, one of the main energy sources; (B) a typical village stove with bake-oven. (Photos by Mislimshoeva, 2013)

TABLE 5 Level of satisfaction with the availability of energy sources.

	Not at all satisfied	Slightly satisfied	Moderately satisfied	Very satisfied	Extremely satisfied
Dung	3	5	91	71	0
Firewood	0	13	115	42	0
Electricity	1	62	51	56	0
Coal	167	1	1	1	0

1990; Mahapatra and Mitchell 1999; Bhatt and Sachan 2004; Johnson and Bryden 2012; Onoja 2012; San et al 2012; Song et al 2012; Rehnus et al 2013). These interactions are dependent on biophysical conditions, socioeconomic and ownership factors, and energy availability.

Elevation plays a critical role in firewood consumption. Whereas Khuman et al (2011) found a decrease in firewood consumption with increasing elevation, most studies have found that firewood consumption increases with increasing elevation (Negi et al 1999; Mustafa and Kaygusuz 2001; Ali and Benjaminsen 2004; Bhatt and Sachan 2004; Förster et al 2011). Our results are consistent with the latter finding. At higher elevations, not only is the heating season longer but also on any given day households need more hours of heating and thus consume more firewood.

More than half of the participating households had members whose highest level of education was education level I. This relates to the Soviet period (ending in 1991), during which colleges for vocational education were the most common places to receive an education beyond school level. This in turn relates to the relatively small size of the 18- to 25-year-old age bracket in the studied villages, as there is an enormous labor migration by young people to Russia due to the lack of job opportunities in the villages. The correlation of firewood consumption with education level I might indicate that households with more educated members use less firewood, but we did not see the same correlation with education level II. One might assume that higher education levels would be associated with a preference for energy-efficient technology; however, almost all households participating in the study used the same heating technology, and almost no houses were insulated. Whether or not the awareness of energy-efficient technologies is related to education level needs to be investigated more explicitly (see an example in Wiedemann et al 2012). Some researchers have shown that education level was a factor influencing firewood use in households in Cambodia and Nigeria (Nnaji et al 2012; San et al 2012).

Household firewood consumption was also correlated to the size of the household's private garden. Private gardens are the largest source of firewood (Figure 4) in the study area; households with larger gardens are able to plant more woody vegetation to meet their firewood needs. This firewood is also free. Indeed, the availability of energy sources influences the level of consumption. However, this is not necessarily the case for all households. Tree species, age, and productivity also play an important role. Further research is needed on extraction of firewood from private gardens.

Some of the study villages receive electricity from the city Khorog and others from a local hydropower station. During winter, electricity is available on alternating days,

FIGURE 4 Firewood sources in winter. Each household extracted firewood from more than one source.

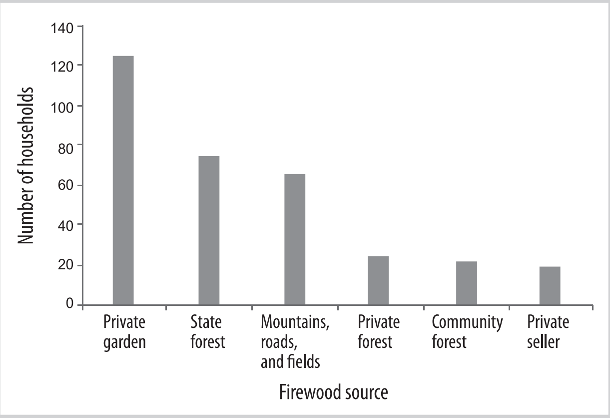
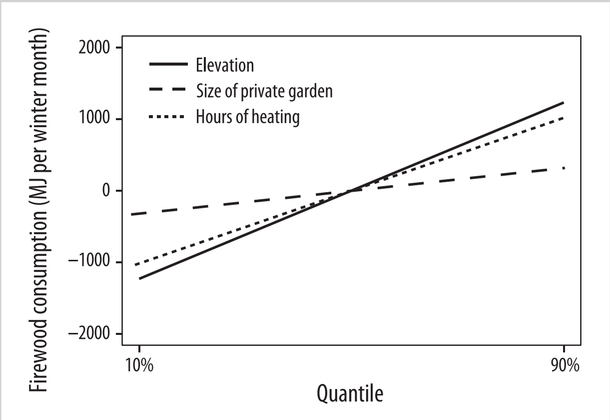


TABLE 6 Ordinary least square coefficients.

Variable	Coefficient
Elevation[a)]	5.69
Education level I[b)]	−888
Size of private garden[a)]	0.489
Electricity supplied from Khorog[b)]	−1200
Hours of heating per month in winter[a)]	11.2

[a)]Continuous variables.
[b)]Categorical variables.

FIGURE 5 Influence of the continuous variables (elevation, size of private garden, and heating hours per month in winter) on firewood consumption. To ensure comparability among results, the scale of each variable ranges from the respective 10% to the respective 90% sample quantile. The coefficients are listed in Table 6.



especially in those villages where electricity is provided locally. The voltage of the locally provided electricity is so low that in some places it is impossible to use for heating and cooking, whereas the electricity provided from Khorog is better. Households that receive electricity from Khorog used less firewood than the others. Electricity did not substitute fully for firewood; rather, it was used for cooking and boiling water, which reduced the pressure on firewood to a certain degree.

Methodological issues

Several limitations remain in this study and suggest potential avenues for future research. First, there is a need for more precise measurement of energy use at the household level, particularly with respect to measuring firewood and dung in the local unit of measure (the bag). Though this seemed to be the easiest way for local people to assess their energy use, it could still be improved, for example, by combining it with other local units and offering different illustrations during the interviews. Nevertheless, this very simple approach to data collection on firewood and dung consumption has great advantages as it is low in cost and easy to apply in any region.

Second, there are some uncertainties associated with the accuracy of the conversion of household-level measurements of firewood and dung amounts. Some of the conversions were based on other studies, thus containing a certain degree of error.

Third, the nature of the interview data, the limitations of the relatively small sample size, and the high number of (potentially) influential variables limit the application of more complex models and more refined statistical analysis.

Finally, it cannot be claimed that the winter of 2011–2012 is representative, as no long-term energy consumption data are available to confirm this. However, the heating season in the study region is usually relatively constant, and thus the obtained quantities of energy consumption give a valuable overview.

In spite of these limitations, this study clearly defines the quantities of different sources of energy, patterns of use, and their relationship with other independent factors.

Conclusions

Energy consumption patterns in the Tajik Pamirs are still far from being fully understood. In particular, the amounts of available energy sources remain unknown. Further research is needed to study the origins of firewood supplies, especially from private gardens and forests. This will allow these sources to be linked to demand in order to explain the wider context of firewood consumption and its impact on land use and land cover.

Though energy consumption differs from village to village, some general patterns can be observed. Findings from this study suggest that in the mountainous areas of the Tajik Pamirs, rural villages depend heavily on animal dung and firewood for winter heating. This dependence varies with elevation and availability of different types of energy, such as electricity and firewood from private gardens. At higher elevations, villages require more energy, as the heating season lasts longer. These are also the most remote villages; they have weak infrastructure, and because of the harsh climatic conditions, there is less biomass. Thus, sustainable energy production efforts such as forestry should be considered.

The trade-offs between energy and food provision may become more extreme as demand for both increases with population growth. Therefore, development of alternative energy sources (for example, small-scale solar energy) is recommended, along with promotion of energy-efficient technology (such as thermal insulation and efficient stoves).

ACKNOWLEDGMENTS

We would like to express our deep gratitude to the people in the villages participating in this study as well as the village leaders, the State Forestry Agency of Gorno Badakhshan, and staff of the GIZ regional program Sustainable Use of Natural Resources in Central Asia. Financial support of this study by the University of Central Asia and the German Academic Exchange Service is gratefully acknowledged. Publication of this article was funded by the German Research Foundation and the University of Bayreuth in the funding program Open Access Publishing. We also thank the 2 anonymous reviewers, the journal editors, and all those who offered valuable comments.

REFERENCES

Ali J, Benjaminsen TA. 2004. Fuelwood, timber and deforestation in the Himalayas. *Mountain Research and Development* 24(4):312–318.
APRS [Automatic Position Reporting System]. World map for APRS in ESRI Shapefile format. http://aprsworld.net/gisdata/world/; accessed on 18 July 2013.
Arrow K, Dasgupta P, Goulder L, Daily G, Ehrlich P, Heal G, Levin S, Mahler KG, Schneider S, Starrett D, Walker B. 2004. Are we consuming too much? *Journal of Economic Perspectives* 18:147–172.
Bhatt BP, Negi AK, Todaria NP. 1994. Fuelwood consumption pattern at different altitudes in Garhwal Himalaya. *Energy* 19(4):465–468.
Bhatt BP, Sachan MS. 2004. Firewood consumption along an altitudinal gradient in mountain villages of India. *Biomass and Bioenergy* 27(1):69–75.
Breckle S, Wucherer W. 2006. Vegetation of the Pamir (Tajikistan): Land use and desertification problems. *In:* Spehn E, Liberman M, Körner C, editors. *Land Use Change and Mountain Biodiversity.* Boca Raton, FL: Taylor & Francis, pp 225–237.
Breu T, Hurni H. 2003. *The Tajik Pamirs: Challenges of Sustainable Development in an Isolated Mountain Region.* Bern, Switzerland: Centre for Development and Environment, University of Bern, and Geographica Bernensia.
Chen L, Heerink N, van den Berg M. 2006. Energy consumption in rural China: A household model for three villages in Jiangxi Province. *Ecological Economics* 58(2):407–420.
Démurger S, Fournier M. 2011. Poverty and firewood consumption: A case study of rural households in northern China. *China Economic Review* 22(4): 512–523.
Dunkerley J, Macauley M, Naimuddin M, Agarwal PC. 1990. Consumption of fuelwood and other household cooking fuels in Indian cities. *Energy Policy* 18(1):92–99.
Falkingham J, Baschieri A, Evandrou M, Grant G. 2009. *Left Behind in Transition? The Well-Being of Older People in Tajikistan.* Discussion paper. London, UK: Centre for Research on Ageing.
Food and Agriculture Organization (FAO). 2013. Units and conversions. http://www.fao.org/docrep/x5667e/x5667e04.htm; http://www.fao.org/docrep/010/ah810e/AH810E13.htm; accessed on 1 June 2013.
Förster H, Pachova NI, Renaud FG. 2011. Energy and land use in the Pamir-Alai Mountains. *Mountain Research and Development* 31(4):305–314.
Friedman J, Hastie T, Tibshirani R. 2010. Regularization paths for generalized linear models via coordinate descent. *Journal of Statistical Software* 33(1):1–22.
Friedman J, Hastie T, Tibshirani R. 2012. Glmnet: Lasso and elastic-net regularized generalized linear models. Boston, MA: Free Software Foundation, Inc. R package version 1.9-3. http://cran.r-project.org/web/packages/glmnet; accessed on 27 May 2013.
Fushiki T. 2009. Estimation of prediction error by using K-fold cross-validation. *Statistics and Computing.* 21(2):137–146.
GIZ [Deutsche Gesellschaft für Internationale Zusammenarbeit]. 2011. *Elaboration of a Value Chain for Firewood in the Tajik Pamirs.* Khorog, Tajikistan: GIZ.
Godfray HC, Crute IR, Haddad L, Lawrence D, Muir JF, Nisbett N, Pretty J, Robinson S, Toulmin C, Whiteley R. 2010. The future of the global food system. *Philosophical Transactions of Royal Society B* 365:2769–2777.
Hastie T, Tibshirani R, Friedman J. 2009. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction.* New York, NY: Springer.
Hoeck T, Droux R, Breu T, Hurni H, Maselli D. 2007. Rural energy consumption and land degradation in a post-Soviet setting—an example from the west Pamir mountains in Tajikistan. *Energy for Sustainable Development* 11(1):48–57.
Hosier RH, Kipondya W. 1993. Urban household energy use in Tanzania: Prices, substitutes and poverty. *Energy Policy* 21(5):454–473.
IDA [Ishkashim District Administration]. 2013. Ishkashim district's statistics. Tajikistan: Gorno Badakhshan Autonomous Oblast.
Imhoff ML, Bounoua L, Ricketts T, Loucks C, Harriss R, Lawrence WT. 2004. Global patterns in human consumption of net primary production. *Nature* 429: 870–873.
Johnson NG, Bryden KM. 2012. Factors affecting fuelwood consumption in household cookstoves in an isolated rural West African village. *Energy* 46(1): 310–321.
Kennes W, Parikht JK, Stolwijk H. 1984. Energy from biomass by socio-economic groups—a case study of Bangladesh. *Biomass* 4:209–234.
Khuman YS, Pandey R, Rao KS. 2011. Fuelwood consumption patterns in Fakot watershed, Garhwal Himalaya, Uttarakhand. *Energy* 36(8):4769–4776.
Kirchhoff J. 2010. *Forestry Sector Analysis.* Eschborn, Germany: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.
Liu S, Costanza R, Farber S, Troy A. 2010. Valuing ecosystem services: Theory, practice, and the need for a transdisciplinary synthesis. *Annals of the New York Academy of Sciences* 1185:54–78.
Mahapatra AK, Mitchell CP. 1999. Biofuel consumption, deforestation, and farm level tree growing in rural India. *Biomass and Bioenergy* 17(4):291–303.
Miehe G, Winiger M, Böhner J, Yili Z. 2001. The climatic diagram map of High Asia. Purpose and concepts. *Erdkunde* 55:94–97.
Mislimshoeva B, Samimi C, Kirchhoff JF, Koellner T. 2013. Analysis of costs and people's willingness to enroll in forest rehabilitation in Gorno Badakhshan, Tajikistan. *Forest Policy and Economics* 37:75–83.
Mustafa FT, Kaygusuz K. 2001. Investigation of the variables effects on fuelwood consumption as an energy source in forest villages of Turkey. *Energy Conversion and Management* 42:1215–1227.
NASA LP DAAC [National Aeronautics and Space Administration, Land Processes Distributed Active Archive Center]. *ASTER Global Digital Elevation Model.* http://gdex.cr.usgs.gov/gdex/; accessed on 18 July 2013.
National Bank of Tajikistan. 2013. http://www.nbt.tj/tj/; accessed on 3 February 2013.
Negi AK, Bhatt BP, Todaria NP. 1999. Local population impacts on the forests of Garhwal Himalaya, India. *Environmentalist* 19:293–303.
Nnaji CE, Uzoma CC, Chukwu JO. 2012. Analysis of factors determining fuelwood use for cooking by rural. *Environmental Sciences* 6(2):1–6.
Onoja AO. 2012. Econometric analysis of factors influencing fuel wood demand in rural and peri-urban farm households of Kogi State. *Sustainable Development* 8:115–127.
Oslon D, Delen D. 2008. *Advanced Data Mining Techniques.* Berlin, Germany: Springer.
R Core Team. 2014. *A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing.
Rehnus M, Nazarek A, Mamadzhanov D, Venglovsky BI, Sorg JP. 2013. High demand for firewood leads to overuse of walnut-fruit forests in Kyrgyzstan. *Journal of Forestry Research* 24(4):797–800.
Samant S, Dhar U, Rawal R. 2000. Assessment of fuel resource diversity and utilization patterns in Askot Wildlife Sanctuary in Kumaun Himalaya, India, for conservation and management. *Environmental Conservation* 27(1):5–13.
San V, Spoann V, Ly D, Chheng NV. 2012. Fuelwood consumption patterns in Chumriey Mountain, Kampong Chhnang Province, Cambodia. *Energy* 44(1): 335–346.
SEEDS [Social Enterprise & Environmental Development Systems]. 2008. *Bio-Mass Energy Use in GBAO.* Khorog, Tajikistan: Social Enterprise & Environmental Development Systems.
SFA [State Forest Agency of Ishkashim District]. 2013. *Land Cover of Ishkashim District, Gorno Badakhshan Autonomous Oblast.* Ishkashim, Tajikistan: State Forest Agency of Ishkashim District.
Sharma CM, Gairola S, Ghildiyal SK, Suyal S. 2009. Forest resource use patterns in relation to socioeconomic status. *Mountain Research and Development* 29(4):308–319.
Singh G, Rawat GS, Verma D. 2010. Comparative study of fuelwood consumption by villagers and seasonal "Dhaba owners" in the tourist affected regions of Garhwal Himalaya, India. *Energy Policy* 38(4):1895–1899.
Song N, Aguilar FX, Shifley SR, Goerndt ME. 2012. Factors affecting wood energy consumption by U.S. households. *Energy Economics* 34(2):389–397.
Tabuti JR, Dhillion SS, Lye KA. 2003. Firewood use in Bulamogi County, Uganda: Species selection, harvesting and consumption patterns. *Biomass and Bioenergy* 25(6):581–596.
Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D. 2001. Forecasting agriculturally driven global environmental change. *Science* 292:8–10.
Wiedemann C, Salzmann S, Mirshakarov I, Volkmer H. 2012. Thermal insulation in high mountainous regions. *Mountain Research and Development* 32(3):294–303.
World Bank. 2009. *Republic of Tajikistan. Poverty Assessment.* Report No. 51341-TJ. Dushanbe, Tajikistan: World Bank.
Zhen L, Liu XL, Wie YJ, Yang L, Long X, Du B, Li F, Cao X. 2011. Consumption of ecosystem services: A conceptual framework and case study in Jinghe watershed. *Resources and Ecology* 2:298–306.

9.

Forest firewood availability and usage: the case of western Pamirs, Tajikistan

Bunafsha Mislimshoeva*[1], Paul Schumacher[1], Cyrus Samimi[2], Thomas Koellner[1]

Planned to be submitted to

Forest Ecology and Management journal

* Corresponding author: bunafsha.mislimshoeva@uni-bayreuth.de

[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstrasse 30, 95447 Bayreuth, Germany

[2] Professorship of Climatology, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth , Universitätsstrasse 30, 95447, Bayreuth, Germany

Forest firewood availability and usage: the case of western Pamirs, Tajikistan

Bunafsha Mislimshoeva*[1], Paul Schumacher[1], Cyrus Samimi[2], Thomas Koellner[1]

* corresponding author: bunafsha.mislimshoeva@uni-bayreuth.de
[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitat str. 30, 95447 Bayreuth, Germany
[2] Professorship of Climatology, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth , Universitat str. 30, 95447, Bayreuth, Germany

Abstract

The effects of firewood extraction on forests' conditions are generally not well understood because firewood availability and usage is very site specific and costly to measure. Forest firewood availability and usages in case of the former Soviet republics, such as Tajikistan is of particular interest. In Soviet times, the demand for forest firewood was relatively low, yet its availability (and usage) were well recorded through inventories by the forestry agencies. After the collapse of the Soviet Union, however, crises in the energy sector have increased dependency on local energy sources (e.g. firewood) while monitoring of firewood availability and usage have become very weak. In this study, we analyze current firewood availability in the forest and its use in the domestic energy sector of Ishkashim district in the Tajik Pamir Mountains. Forest firewood Mean Annual Increment (MAI) was put in relation to households' usage in the five forest sites and villages. The results show that overall, there is a positive balance between forest firewood availability and usage which suggests that firewood deficiency may not occur in the case study areas. This however, needs to be interpreted with caution in practice, as local heterogeneity plays in important role.

Keywords: forest biomass increment, villages, firewood availability and usage, scenarios.

1. Introduction

Although research on ecosystem services has grown rapidly in recent years, important aspects such as source of service provision, benefiting areas, and the flow between them is explicitly addressed only in a few studies (e.g. García-Nieto et al., 2013; Serna-Chavez et al., 2014). To date there seems to be no systematic approach to this issue and more research is needed to deliver consistently described, policy-relevant outcomes (Scarlettt and Boyd, 2011; Villa et al., 2012; Abson et al., 2014).

In the context of developing countries, one of the most important forest's provisioning services is firewood. Availability and usage of this service remains subject of a heated debate. This is firstly due to the fact, that firewood availability and usage is very site specific (Arnold and Persson, 2003; Arnold et al., 2003; Masera et al., 2006; Ghilardi et al., 2009). To deal with this challenge, studies considering the local energy heterogeneity have been carried out in different regions. The results of these studies were then aggregated to explain and interpret the firewood energy situation on a national level (Allen et al., 1988; Top et al., 2004a; Top et al., 2004b; Masera et al., 2006; Devi et al., 2009; Rehnus et al., 2013). For example, in developing countries more than two billion people depend on wood for cooking and heating in their daily life (FAO, 2010). However, this is very broadly aggregated information at coarse scales, and household firewood usage at local scales in different countries remains largely unknown in many countries. Secondly, even though several developing countries have established reliable assessments of national firewood availability and usage (Arnold and Persson, 2003), the applied methodologies remain very costly for others (Kituyi et al., 2001; Masera et al., 2006). Thus, inconsistent and sometimes very poor records exist about forest firewood production, while almost no research has been done outside of forests. For example in some former Soviet Union countries last forestry inventory dates back to the 80s or 90s of 20th century. Because of these two above-mentioned reasons the impact of firewood extraction on forests' conditions is still not well understood.

Quantifying firewood availability and usage in case of former Soviet republics is of particular importance. During Soviet times, local people and institutions were supplied with sufficient amounts of fuel such as coal and diesel. Even though domestic demand for firewood was very low, its availability and usage in the forest was well recorded by the forestry sector agencies. After the collapse of the Soviet Union in 1991, lack of finance and crisis in the energy sector increased local population's dependence on local energy sources. Hence, the demand for firewood has increased steadily, but there is very little knowledge on sustainable firewood availability and usage.

One such country is Tajikistan, where only a few studies have been conducted on domestic firewood consumption (Hoeck et al., 2007; Mislimshoeva et al., 2014). In contrast, the quantification of production from different sources remains largely unknown. After private gardens, forests are the second biggest source of firewood in the domestic energy sector in rural areas (Mislimshoeva et al., 2014).

Firewood availability and usage is particularly important for mountainous areas of Tajikistan due to their remoteness, socio-economic conditions and limited access to alternative energy sources. Understanding forest firewood availability and usage patterns is crucial for sustainable forests management, as it would allow allocating this scarce resource efficiently. Thus, the aim of this study is to analyze forest firewood availability and usage in the domestic energy sector in Ishkashim district. We expect that, overall there is forests overuse through firewood extraction. We draw this assumption from own long-term experience in the region and from existing literature which mostly investigated this topic qualitatively (Breu and Hurni, 2003; Droux and Hoeck, 2004; Breckle and Wucherer, 2006; Hoeck et al., 2007; World Bank 2007; Kirchhoff and Fabian, 2010; Ibele et al., 2012; Shigaeva et al., 2013). Further, we adapt a quantitative framework for assessing spatial flows of ecosystem services (Serna-Chavez et al., 2014) and analyze weather villages closer to the forest utilize more firewood than those located farer away.

2. Material and methods

2.1 Study area

2.1.1 Geography and population

In Tajikistan 73% of the eight million inhabitants live in rural areas (World Bank, 2014a; 2014b). Consequently, the largest portion of total firewood energy demand is in these areas (UNDP, 2013). The research area, Ishkashim district, is located in the western part of the Tajik Pamirs (also called Gorno-Badakshan Autonomous Oblast) (Fig. 1). This area represents a typical remote mountainous region, as people depend on local scares energy sources in wintertime. The continental dry climate is shaped by high mountains with an elevation spectrum of 2000 to 7500 meters above sea level (m asl). In wintertime, minimum temperatures of -2°C to -8°C in the valleys typically occur in January (Miehe et al., 2001; Breu and Hurni, 2003; Breckle and Wucherer, 2006). Biomass production is severely limited in the region because of the low precipitation and the harsh temperature regimes as well as the vegetation period of 200-230 days per year (Droux and Hoeck, 2004).

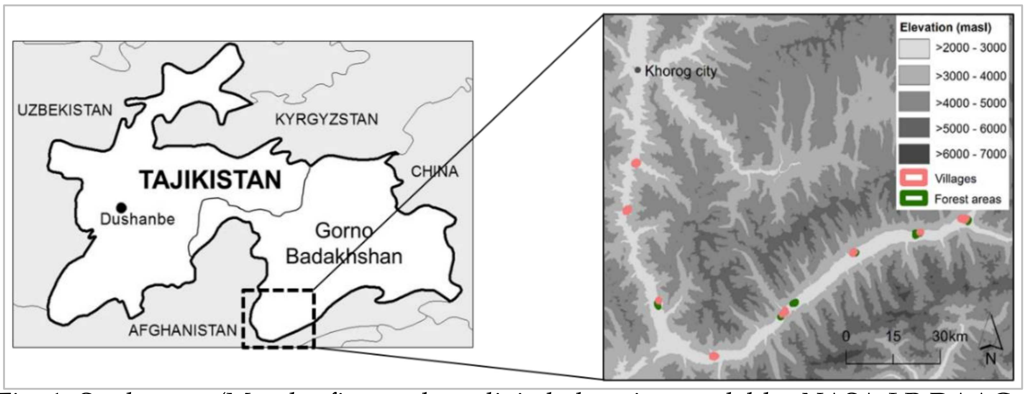


Fig. 1. Study area (Map by first author; digital elevation model by NASA LP DAAC, 2013; country border line by APRS, 2013)

There are 47 villages with approximately 25,000 inhabitants in the district, with the number of households ranging from 15 to 260. Farming and livestock breeding are the main occupations, and a few households are engaged in forestry (for a more detailed description of the study area see Mislimshoeva et al., 2014).

2.1.2 Energy usage

During Soviet Union times, energy sources such as coal, kerosene, diesel and gas were highly subsidized (Herbers, 2001) in the Tajik Pamirs. Hydropower was produced locally and provided even to the remotest areas of the region (Breu and Hurni, 2003). Parallel to this reforestation and afforestation campaigns were carried out, starting around 1940. After the seven years of civil war that had followed the independence of Tajikistan in 1991, the constant energy supply (mainly coal, gas, and fuel) had abruptly stopped. The resulting pressure on scarce local resources, especially forests, increased dramatically as local people and institutions lacked alternative sources of energy (Fig. 2).

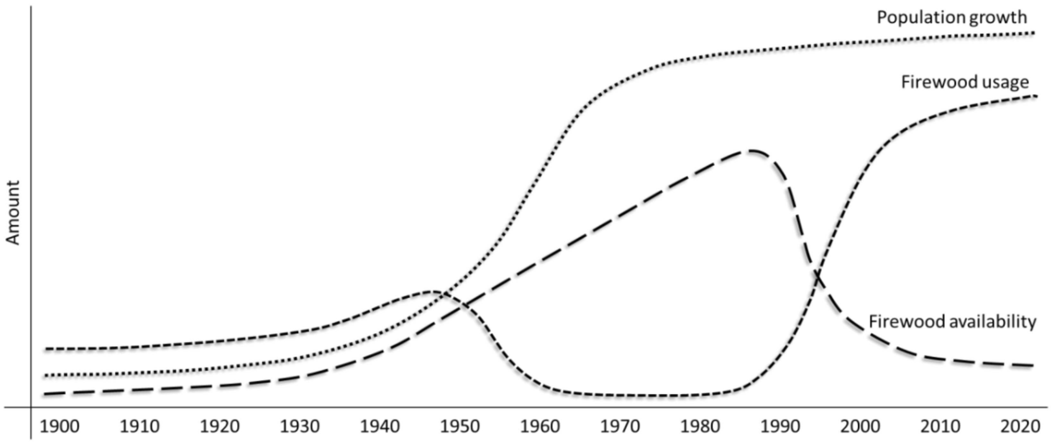


Fig. 2. In the absence of numeric data (especially the last 30 years), this figure presents the schematic model of firewood availability and usage in Tajikistan since 1900. The curves are estimations based on literature review, personal communication and common knowledge. The sharp decline of firewood availability and increase of usage took place during the years of civil war in the 1990s (adapted from Hoeck, et al. 2007).

Heating durations in the study region vary with altitude. In higher altitudes (2800 m asl) households heat their homes for up to six months, while at mid-altitudes (2650 m asl) and lower altitudes (2450m asl) the heating duration drops to five and four months respectively. In the heating season, dung and firewood are the main sources of energy. Dung is available in almost every household (Mislimshoeva et al., 2014). Firewood is mainly extracted from private gardens, forests, as well as gorges, roadsides and around agricultural land (Table 1).

Table 1: Overview on different sources of firewood in the Western Pamirs

Source of firewood	Description
Natural and planted state forest areas under Post-Soviet Management system	These forests belong to the Forestry Agency (FA). Typically they are managed by the FA without involvement of local people. The FA employs one or two foresters in each community, in order to manage the neighbouring forest plots. Under this management system, local population purchase "firewood ticket" from the FA and harvest a certain volume in a forest plot selected by the FA/foresters. Since the collapse of the Soviet Union, the number of permanent foresters in Tajikistan has decreased drastically. However, the so-called "seasonal workers" are involved during the spring and autumn working-seasons. Both, foresters and seasonal workers receive extremely low salary from in cash or kind (forest products) (SPCT, 2015; Mislimshoeva et al., 2016).
Natural and planted state forest areas under recently introduced Joint Forest Management (JFM)	These forests belong to the FA as well, however, are managed jointly with local population. Interested local people lease a certain forest plot from the state for the period of 20 years, with prolongation opportunity. The core parts of this management types are the contract and the concrete management plans, considering the principles of sustainable forestry. The local tenants do not receive cash salary, however, have legal user rights of forest use and in turn care for protection and rehabilitation of forests. JFM has been introduced since 2007 and the number of tenant is growing currently
Natural and planted community (association) forests	The so called "association forests" belong to a certain village/community. The community leader is responsible for overall forest management, however, supported by the local population especially during the working season in spring. Every household of the community has equal rights to harvest firewood in the forest.
Private gardens	In the private gardens each household commonly plant fruit trees, however, in some cases it is also combined with poplar and willow trees for construction or firewood purposes. In the case study region, each household owns a garden.
Gorges, roadsides and around agricultural land	Local population in the remote areas collect firewood in the mountains along the streams, roadsides and/or around agricultural land.

2.1.3 Forest area and management

In the western Pamir's riparian forests (also known as small-leaved forests) are the most dominant at an elevation from 1500 to 3000 m asl to anthropogenic influence (Fig. 3). Both, natural forests and irrigated plantations can be found in the floodplains of the riverbanks. These forests provide several ecosystem goods and services, and are a crucial spot of biodiversity in the region (Kirchhoff and Fabian, 2010). The main species growing in the riparian forests are willow (*Salix turanica, Salix shugnanica, Salix wilhelmsiana and Salix babylonica*), poplar (*Populus pyramydalis and Populus pamirica*) and sea-buckthorn (*Hippophae rhamnoides*). Roughly, 2300 ha are designated as forest in the district; but only approximately 1800 ha are actually covered by trees. The remaining 500 ha are currently bare soil and sand dunes (FA, 2013). In most of the forest plots, a Joint Forest Management (JFM) approach has been implemented since 2007, and these forest plots are state owned (for more description of the approach see Mislimshoeva et al., 2013). According to this approach, the Forestry Agency and local people (i.e. tenants) share the responsibilities and benefits. Typically, each forest plot under JFM is assigned to a village and build a pair – plot and village. The same pairwise approach is true for community forests, where the community next to a forest plot manages it and benefits from its goods.

Fig. 3. Riparian forest in the Ishkashim district. Photos: Mislimshoeva, 2013

2.2 Research framework

In order to spatially illustrate the flow of forest firewood availability and usage, our research framework is based on Serna-Chavez et al. (2014), who suggests a generic framework of spatial relationships between provisioning and benefiting areas of ecosystem services. The authors illustrate the application of the framework with global data on pollination, water provision and climate regulation services. Also, the authors discussed the possible application of the framework for other services and other spatial scales. As the framework for provision of food and raw materials (Serna-Chavez et al., 2014) seems to be amenable to fine-tuning in order to suit specific conditions, we therefore adapted and simplified it according to the scale and context of this study (see Fig. 4).

The green circle with *P* in Fig. 4, represents service provisioning areas i.e. forests. The red circle with *V*, represents the primary benefiting village, and the F is the flow area within which the services from provisioning area are delivered to the primary village.

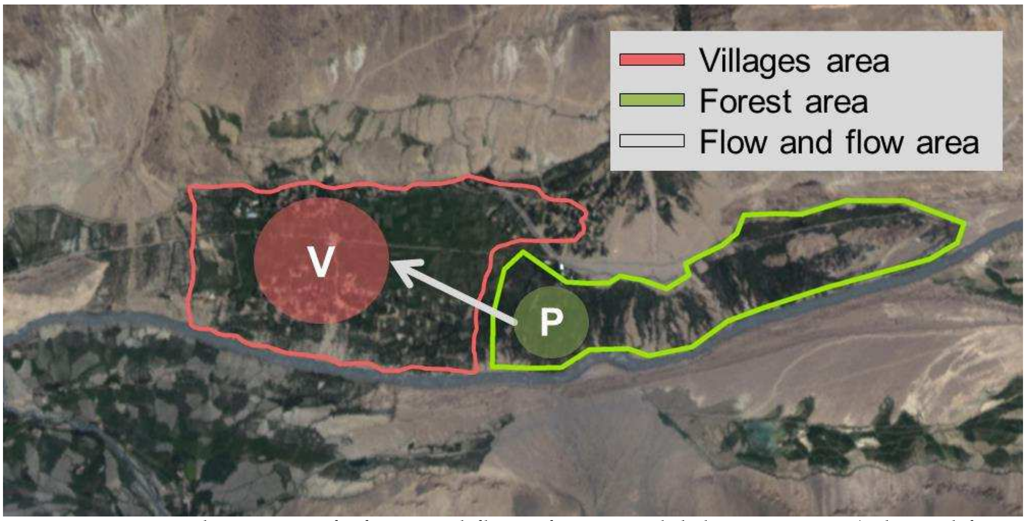


Fig. 4. Framework to quantify firewood flows from availability to usage (adapted from Serna-Chavez et al., 2014)

2.3 Forest availability - usage data and analysis

Two published reports have estimated forest Mean Annual Increment of 3-8 m^3 ha^{-1} $year^{-1}$ (Novikov and Safarov, 2003) and 10 m^3 ha^{-1} $year^{-1}$ (for *Salix* and *Populus* species) respectively (Kirchhoff, 2009). We used their figures in the analysis as a baseline for forest biomass increment. As an average, MAI of 3-8 m^3 ha^{-1} $year^{-1}$ we draw 5.5 m^3 ha^{-1} $year^{-1}$ and included in the analysis as a first scenario. The second scenario was the MAI of 10 m^3 ha^{-1} $year^{-1}$. Each of these two scenarios was multiplied by the size of each forest plot in order to estimate the total m^3 $plot^{-1}$ $year^{-1}$ MAI. The MAI of each forest plot was then used to generate random distribution and with a standard deviation equal to 10%. The created dataset was utilized in the budget estimation between forest biomass increment (firewood availability) and households' firewood usage. In summary, two literature-based MAI were used in the analysis in this study (Novikov and Safarov, 2003; Kirchhoff, 2009).

Mislimshoeva et al. (2014) estimated the overall firewood usage in eight villages in the Ishkashim district through households' interviews. Out of these, five were primary villages i.e. those assigned to a forest site or the so called direct beneficiaries (see Fig. 4 and Table 2). In these villages the household's average firewood usage was multiplied by the total number of households in the village in order to estimate the overall village firewood usage. Furthermore, it was converted to m^3 for the purpose of this study (for more detailed conversions see Mislimshoeva et al., 2014).

Table 2 Case study areas sorted according to elevation from 2800m asl to 2400m asl. (forest firewood usage data is derived from Mislimshoeva et al., 2014). *Households; **Distance between the village and forest.

Village / Forest Area	m^3 hh^{-1} year^{-1}	Heating period	Total HH*	Surveyed HH	Forest area size (ha)	Distance** (m)
Hisor	1.32	6	98	32	72	700
Drij/ Drij-Nigar	1.74	6	58	23	83	1150
Tugoz	3.51	5	57	23	13	900
Darshay/ Dar.-Nar.	3.75	5	58	23	59	4000
Sumjin	5.2	4	41	16	24	1500
Total			**312**	**117**		

The budget (B_i) between biomass increment of a forest plot (IFP_i) of two scenarios and households' firewood usage (HFU_i) was estimated as following:

(1) $B_i = IFP_i - HFU_i$

For estimating the standard errors (derived from standard deviation) of the forest and village budget of each case, we performed bootstrapping method (Efron and Tibshirani, 1993; Field et al., 2012) with 5000 replications in statistical software – R, package bootstrap (version 3.2.3; R Core Team 2015; Efron and Tibshirani, 1993). The mean and standard errors for each individual budget was then plotted for illustration (95% confidence intervals). For analysing the spatial flow from forest area to the village, the distance between the village and the forest areas was taken into account.

3. Results

3.1 Forest biomass increment and households firewood usage

Under the first scenario (5.5 m^3 ha^{-1} year^{-1}) on average, there is 276 m^3 plot^{-1} year^{-1} Mean Annual Increment of forest biomass. The minimum and maximum MAIs are 72 m^3 plot^{-1} year^{-1} and 457 m^3 plot^{-1} year^{-1}. The average MAI is 502 m^3 plot^{-1} year^{-1} according to the second scenario (10 m^3 ha^{-1} year^{-1}), while the minimum and maximum are 130 m^3 plot^{-1} year^{-1} and 830 m^3 plot^{-1} year^{-1} (Fig. 5, a).

In the investigated villages in Mislimshoeva et al. (2014), the amount of households' firewood usage which originated in the forests was extracted from the overall firewood usage in each village. On household level, the average forest firewood usage ranges from 1.3 to 5.7 m^3 hh^{-1} $winter^{-1}$ having the mean of 3 m^3 hh^{-1} $winter^{-1}$. In the studied villages, the proportion of firewood, extracted from the forest varies among the villages as Fig 5 (b) presents. The distance between the villages and the forest area does not play a significant role.

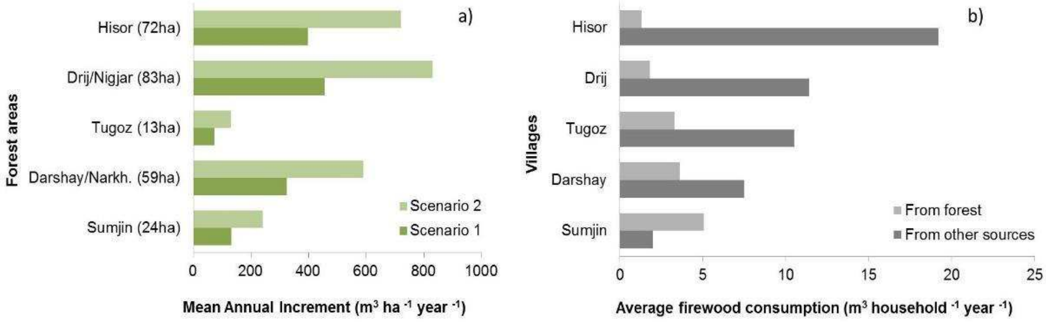


Fig. 5. a) Mean Annual Increment of scenario 1 (5.5 m^3 ha^{-1} $year^{-1}$ (Novikov and Safarov, 2003)) and scenario 2 (10 m^3 ha^{-1} $year^{-1}$ (Kirchhoff, 2009)). b) Average firewood usage of a household per winter in the studied villages. Villages are sorted according to elevation from 2800m asl to 2400m asl. (forest firewood usage data is derived from Mislimshoeva et al., 2014).

3.2 Relationship between forest biomass increment and firewood usage

Using two increment estimation scenarios presented in Fig. 5 (Novikov and Safarov, 2002; Kirchhoff, 2009) the relation with the average villages' usage was analyzed. Although the balance between forest biomass increment and firewood usage varies from village to village, overall, the results seem to demonstrate a positive balance in almost all studied villages (Fig. 6). Out of five forest plots/villages, under the first scenario, there is one case (Tugoz case study) with a negative budget, while under the second scenario there seems to be no case with negative budget.

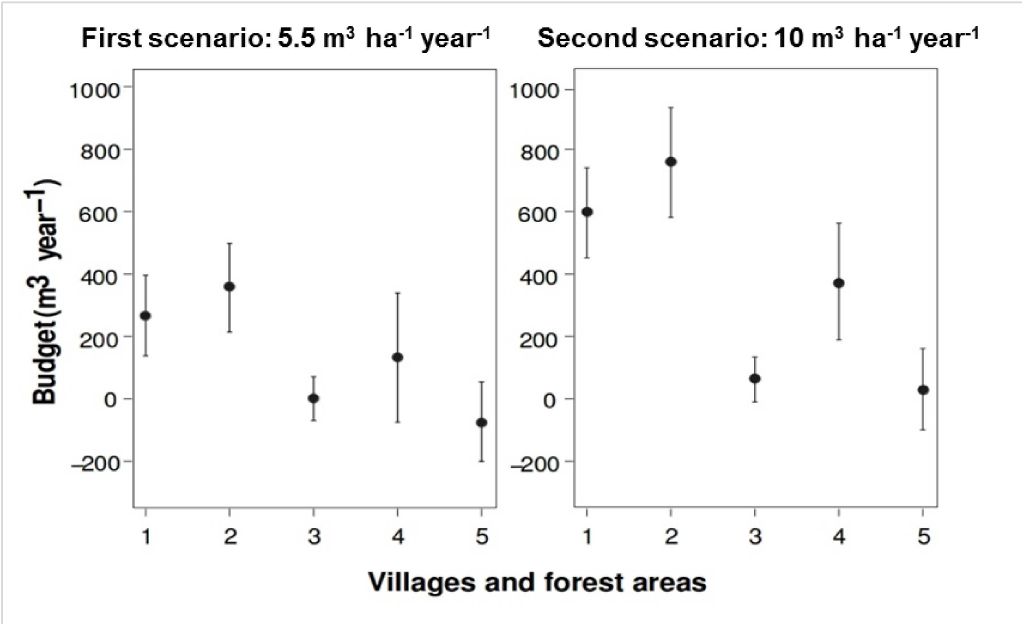


Fig 6. Budgets of firewood availability and usage as a result of bootstrapping (95% confidence intervals). Legend of case studies: 1 – Hisor; 2 – Drij: 3 – Tugoz; 4 – Darshay/Narkhun; 5 – Sumjin.

4. Discussion

In this study, we analyzed forest firewood availability and usage in the mountainous areas of Tajikistan district Ishkashim. Our estimations of firewood per capita per winter day on average is 0.5±0.1 kg at the altitudes of 2400-2800m asl. In contrast, other studies found higher numbers for firewood usage. For example, Bhatt and Sachan (2004) analyzed firewood consumption at different altitudinal gradient in mountainous villages of India. The authors report firewood from 1.1 to 2.80 kg/capita/day, respectively, from 500 to 2000m asl in different case studies. Sharma et al., (2009) carried out a similar study in Garhwal Himalaya, and showed 2.7, 2.3, 3.4, and 4.4 kg/capita/day in four researched villages. Rehnus et al., (2013) showed 3.90 kg/capita/heating day in case studies in Kyrgyzstan, highlighting the pressure on forest resources. The significant difference between the finding of this study and those from comparable regions is that forests are not the only source of firewood in the study region. Part of firewood is extracted from the forests, however, the most important source of firewood in the research are private gardens of households, where firewood is extracted free of charge (Mislimshoeva et al., 2014). However, studies on quantifying private garden as a source of energy are absent in the study region and further research outlook on this is mentioned in Mislimshoeva et al., 2014. There are local heterogeneities such as number of households, heating duration, altitude and distance to the forest, which need to be taken into account. Top et al. (2004a) for example, found out that firewood extraction from forest is largely influenced by the distance between forest and village. The current study shows that firewood availability and usage is not dependent on the distance to the forest area, as most of the case study areas are located closely to the forest.

The results of this study seem to demonstrate a positive balance between forest firewood availability and usage in almost all cases in the research area. A possible explanation for this could be that there are some uncertainty related to the firewood conversions of bag units into m^3, which is fully discussed in Mislimshoeva et al., 2014. Furthermore, during the interviews, households mentioned only the amount of firewood that they officially bought from the Forestry Agency. There are no recorded available data on illegal firewood extraction in the forest. Thus, despite this to be an important piece of information, our study lacks these data in the firewood usage estimation. Moreover, livestock influence on forest growth is relatively high in the region; but since there no quantitative data on this behalf, it was not included in the analysis. We assume that, if these missing data were included in the analysis, the firewood availability and usage relation would result in more negative or imbalanced cases. Due to these mentioned reasons, the positive balance between forest firewood availability and usage has to be interpreted with caution for practical use.

5. Conclusions

Firewood availability and usage balance is very heterogeneous among forest plots/villages in the study region. Overall, the results show a positive balance between forest firewood availability and usage. This however, has to be interpreted with caution if used for forest management practices. The data of firewood usage data of this study contain some uncertainties, which are underlined in the discussion in detailed. Furthermore, scale dependency is crucial and should be addressed in decision-making, as firewood availability and usage is site-specific. Forest firewood allocation should be considered at the local (e.g. village) scale.

Even with some uncertainties, this study still can serves a source of information for decision makers on forest management in the studied district and those with similar conditions. Taking into account the limitation and uncertainties of this study, future research is needed on improved methodologies, coupling spatial and temporal data. The specific research outlook will be focused on integrating satellite-images–based Mean Annual Increment estimation, which provides the opportunity to spatially analyze forest firewood availability and usage. This can possibly extended also towards temporal analysis, which is subject to data availability.

Firewood availability question will remain a relevant issue in the mountainous areas in Tajikistan and in other regions with similar conditions, as local people heavily depend on it. It is a matter of fact that with the population growth, which will double by 2050 (UN, 2015) the available energy source will become scarcer in Tajikistan, given the limited natural resources. Although other sources of energy such as animal dung, electricity and coal are typically used in daily life in the study area, development of alternative energy sources such as solar needs to be considered on one side and of energy-efficient measures on the other side. Furthermore, improved forest governance plays a key role in creating more firewood sources in the region.

Acknowledgements

We are grateful to all for their invaluable comments and suggestions on the first draft of this manuscript. We acknowledge the Forestry Agency of Gorno Badakhshan for their valuable advices. We also thank the University of Central Asia and the German Academic Exchange Service for their financial support.

References

Abson, D.J., von Wehrden, H., Baumgärtner, S., Fischer, J., Hanspach, J., Härdtle, W., Heinrichs, H., Klein, A.M., Lang, D.J., Martens, P., Walmsley, D., 2014. Ecosystem services as a boundary object for sustainability. Ecol. Econ. 103, 29–37. doi:10.1016/j.ecolecon.2014.04.012

Allen, J.A., Pimentel, D.P., Lasoie, J.P., 1988. Fuelwood production and use in rural Swaziland: A case-study of two communities. Forest Ecol. Manage. 25(3-4), 239–254. doi:10.1016/0378-1127(88)90090-4

APRS (Automatic Position Reporting System). World map for APRS in ESRI Shapefile format. http://aprsworld.net/gisdata/world/; (accessed July 2014).

Arnold, M., Persson, R., 2003. Reassessing the fuelwood situation in developing countries. Int. For. Rev. 5(4), 379-383. doi:10.1505/IFOR.5.4.379.22660

Bhatt, B.P., Sachan, M.S., 2004. Firewood consumption along an altitudinal gradient in mountain villages of India. Biom. Bioener. 27(1): 69–75.

Breckle, S., Wucherer, W., 2006. Vegetation of the Pamir (Tajikistan): Land use and desertification problems. In: Spehn E, Liberman M, Körner C, editors. land use change and mountain biodiversity. Boca Raton, FL: Taylor and Francis, pp 225–237.

Breu, T., Hurni, H., 2003. The Tajik Pamirs: Challenges of Sustainable Development in an Isolated Mountain Region. Centre for Development and Environment (CDE), University of Berne. Berne.

Devi, R., Singh, V., Dahiya, R. P., Kumar, A., 2009. Energy consumption pattern of a decentralized community in northern Haryana. Renew. Sustain. Ener. Rev. 13(1), 194–200. doi:10.1016/j.rser.2007.05.007

Droux, R., Hoeck, T., 2004. Energy for Gorno Badakhshan: hydropower and the cultivation of firewood. Analysis of the energy situation in the Tajik Pamirs and its consequences for land use and natural resource management. (Joint Diploma Thesis). University of Berne.

Efron, B., Tibshirani, R., J., 1993. An introduction to the Boostrap. Chapman and Hall/CRC Press LLC, Florida, US.

Field, A., Miles, J., Field, Z., 2012. Discovering statistics using R. SAGE Publication LtD, London.

García-Nieto, A., P., García-Llorente, M., Iniesta-Arandia, I., Martín-López, B., 2013. Mapping forest ecosystem services: From providing units to beneficiaries. Ecosyst. Serv. doi:10.1016/j.ecoser.2013.03.003

Ghilardi, A., Guerrero, G., Masera, O., 2009. A GIS-based methodology for highlighting fuelwood supply/demand imbalances at the local level: A case study for Central Mexico. Biom. Bioener. 33(6-7), 957-972. doi:10.1016/j.biombioe.2009.02.005

Herbers, H., 2001. Transformation in the Tajik Pamirs: Gornyi-Badakhshan – an Example of Successful Restructuring? Cent. Asian Surv. 3,367–381.
Hoeck, T., Droux, R., Breu, T., Hurni, H., Maselli, D., 2007. Rural energy consumption and land degradation in a post-Soviet setting—an example from the west Pamir mountains in Tajikistan. Ener. Sustain. Dev. 11(1), 48–57.
Ibele, B., Fabian, A., Donga, M., Michel, S., 2012. Linking natural resource management and adaptation to climate change. Experiences from the Tajik Pamirs. Eschborn.
Kirchhoff, J., 2009. Sustainable rehabilitation and development of floodplain forests in Gorno-Badakhshan, Tajikistan. Report. Khorog.
Kirchhoff, J., Fabian, A., 2010. Forestry Sector Analysis of the Republic of Tajikistan. Deutsche Gesellschaft fuer Technische Zusammenarbeit (GTZ) GmbH. Dushanbe.
Kituyi, E., Marufu, L.,Wandiga, S.O., Jumba, I.O., Andreae, M.O., Helas, G., 2001. Biofuel availability and domestic use patterns in Kenya. Biom. Bioener. 20, 71–82.
LP DAAC (NASA Land Processes Distributed Active Archive Center). ASTER Global Digital Elevation Model. http://gdex.cr.usgs.gov/gdex/; accessed July 2014.
Masera, O., Ghilardi, A., Drigo, R., Angel, M., 2006. WISDOM : A GIS-based supply demand mapping tool for woodfuel management. Biom. Bioener. 30, 618-637. doi:10.1016/j.biombioe.2006.01.006
Miehe, G., Winiger, M., Böhner, J., Yili, Z., 2001. The climatic diagram map of High Asia. Purpose and concepts. Erdkd. 55:94–97.
Mislimshoeva, B., Hable, R., Fezakov, M., Samimi, C., Abdulnazarov, A, Koellner, T., 2014. Factors influencing households ' firewood consumption in the Western Pamirs , Tajikistan. Mt. Res. Dev. 34(2), 147–156.
Mislimshoeva, B., Samimi, C., Kirchhoff, J.-F., Koellner, T., 2013. Analysis of costs and people's willingness to enroll in forest rehabilitation in Gorno Badakhshan, Tajikistan. For. Pol. Econ. 37, 75–83. doi:10.1016/j.forpol.2012.12.001
Novikov, V., Safarov,N., 2003. State of the Environment inTajikistan. http://enrin.grida.no/htmls/tadjik/soe2001/eng/htmls/forest/state.htm; (accessed May 2014).
R Core Team. 2015. A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing.
Rehnus, M., Nazarek, A., Mamadzhanov, D., Venglovsky, B.I., Sorg, J.P., 2013. High demand for firewood leads to overuse of walnut-fruit forests in Kyrgyzstan. J For. Res. 24(4), 797–800.
Scarlett, L., Boyd, J., 2011. Ecosystem Services: quantification, policy applications, and current federal capabilities. Discussion paper. Washington DC.
Serna-Chavez, H., M., Schulp, C., Van Bodegom, P., M., Bouten, W., Verburg, P., H., Davidson, M., D., 2014. A quantitative framework for assessing spatial flows of ecosystem services. Ecol. Indic. 39, 24–33.

Sharma, C.M., Gairola, S., Ghildiyal, S.K., Suyal, S., 2009. Forest Resource Use Patterns in Relation to Socioeconomic Status. Mt. Res. Dev., 29(4), 308–319. doi:10.1659/mrd.00018

Shigaeva, J., Wolfgramm, B., Dear, C., 2013. Sustainable Land Management in Kyrgyzstan and Tajikistan: A Research Review. MSRI Background Paper No. 2. http://msri.ucentralasia.org/events.asp?Nid=589

SPCT (Союз профессиональных консультантов Таджикистана) (Union of Professional Consultants Tajikistan), 2013. Комплексный Анализ Лесного Сектора Республики Таджикистан (Comprehensive Analysis of the Forestry Sector of the Republic of Tajikistan. Report. Dushanbe) (in Russian)

Top, N., Mizoue, N., Ito, S., Kai, S., 2004a. Spatial analysis of woodfuel supply and demand in Kampong Thom Province, Cambodia. For. Ecol. Manage. 194(1-3), 369–378. doi:10.1016/j.foreco.2004.02.028

Top, N., Mizoue, N., Kai, S., 2004b. Estimating forest biomass increment based on permanent sample plots in relation to woodfuel consumption: a case study in Kampong Thom Province, Cambodia. J For. Res. 9(2), 117–123. doi:10.1007/s10310-003-0064-9

UN (United Nations), 2015. Tajikistan total population projections. http://esa.un.org/unpd/wpp/Graphs/Probabilistic/POP/TOT/ (accessed July 2015).

Villa, F., Bagstad, K., Johnson, G., Voigt, B., 2012. Towards a comprehensive approach to quantifying and mapping ecosystem services flows. Basque Centre for Climate Change (BC3). BC3 Working Paper. Spain.

World Bank, 2007. Integrating Environment into Agriculture and Forestry Progress and Prospects in Eastern Europe and Central Asia. Country review. Tajikistan.

World Bank, 2014a. Tajikistan. http://www.worldbank.org/en/country/tajikistan; (accessed June 2014)

World Bank, 2014b. Rural population. http://search.worldbank.org/quickview?name=%3Cem%3ERural%3C%2Fem%3E+%3Cem%3Epopulation%3C%2Fem%3E+%28%25+of+total+%3Cem%3Epopulation%3C%2Fem%3E%29&id=SP.RUR.TOTL.ZS&type=Indicators&cube_no=2&qterm=rural+population; (accessed June 2014)

10.

Woody biomass estimation in semi-arid high mountainous region using high-resolution red edge and texture satellite features

Paul Schumacher [1,*], Bunafsha Mislimshoeva [1,5], Alexander Brenning [2], Harald Zandler [3], Martin Brandt [4], Cyrus Samimi [3,5], and Thomas Koellner [1,5]

Planned to be submitted to

Remote Sensing journal

[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Geosciences, University of Bayreuth, 95440 Bayreuth, Germany

[2] Department of Geography, Friedrich Schiller University, 07743 Jena, Germany

[3] Institute of Geography, University of Bayreuth, 95440 Bayreuth, Germany

[4] Department of Geosciences and Natural Resource Management, University of Copenhagen, 1017 Copenhagen, Denmark

[5] Bayreuth Center of Ecology and Environmental Research (BayCEER), University of Bayreuth, 95440 Bayreuth, Germany

* Author to whom correspondence should be addressed; E-Mail: paul.schumacher@posteo.de;

Manuscript

Woody biomass estimation in a semi-arid high mountainous region using high-resolution red edge and texture satellite features

Paul Schumacher [1,*], Bunafsha Mislimshoeva [1,5], Alexander Brenning [2], Harald Zandler [3], Martin Brandt [4], Cyrus Samimi [3,5], and Thomas Koellner [1,5]

[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Geosciences, University of Bayreuth, 95440 Bayreuth, Germany

[2] Department of Geography, Friedrich Schiller University, 07743 Jena, Germany

[3] Institute of Geography, University of Bayreuth, 95440 Bayreuth, Germany

[4] Department of Geosciences and Natural Resource Management, University of Copenhagen, 1017 Copenhagen, Denmark

[5] Bayreuth Center of Ecology and Environmental Research (BayCEER), University of Bayreuth, 95440 Bayreuth, Germany

***** Author to whom correspondence should be addressed; E-Mail: paul.schumacher@posteo.de;

Abstract

Remote sensing based biomass quantification in sparsely vegetated areas is often limited when using only common broadband vegetation indices as input data for correlation with ground measured biomass information. Red edge indices or texture attributes are often suggested to tackle this issue. However, clear recommendations on the suitability of specific proxies to provide accurate biomass information in semi-arid to arid environments are still lacking. This study contributes to the understanding of the interrelationship between multispectral high-resolution satellite data (RapidEye), using red edge and texture attributes, and ground-measured woody biomass in semi-arid ecosystems with scarce woody vegetation. LASSO (Least Absolute Shrinkage and Selection Operator) and Random Forest were used as predictive models relating aboveground standing woody biomass to satellite data. Model performance was evaluated based on cross-validation bias, standard deviation and Root Mean Square Error (RMSE) at the logarithmic and non-logarithmic scales. Both models achieved rather limited performances in woody biomass prediction. Nonetheless, model performance increased with red edge indices and texture attributes, which shows that they play an important role in semi-arid regions with sparse vegetation.

Keywords: woody biomass estimation, semi-arid, RapidEye, red edge, texture attributes

1. Introduction

Standing biomass in semi-arid to arid regions plays a significant role as it prevents soil erosion and degradation, can be considered as important carbon pool due to the vast extent of drylands over the Earth's land surface, and it is a year round source for firewood as well as for construction timber for the local population (Bombelli et al. 2009, Lu 2006, MEA 2005, Safriel and Adeel 2005, UNEP 2012). For gaining quantitative information on above ground biomass, the utilization of remote sensing based applications has become increasingly feasible in recent years. Earth Observation (EO) data sets are available for large areas and rapid advances in remote sensing techniques allow fast, frequent and continuous biomass observations over various scales in time and space (Ayanu et al. 2012, Sarker and Nichol 2011). As optical EO data alone cannot directly measure reliable quantitative biomass information (Eisfelder et al. 2012), a common approach has become to correlate satellite-derived parameters, primarily Vegetation Indices (VIs) measuring photosynthetic vigour, with ground measured biomass information (e.g. Avitable et al. 2012, Cutler et al. 2012, Samimi and Kraus 2004, Zandler et al. 2015a). This allows an indirect prediction of quantitative biomass information.

In regions with high biomass levels, such as tropical or boreal regions, remote sensing studies of vegetation are more comprehensive than in semi-arid to arid savannahs or shrublands (Eisfelder et al. 2012). However, in environments where sparse and woody vegetation is predominant, remote sensing techniques face specific challenges and additional methodological research is needed (Asner et al. 2000, Beeri et al. 2007, Qi and Wallace 2002, Svoray and Shoshany 2003, Wessels et al. 2006). Studies found that especially the use of common broadband VIs such as NDVI (Normalized Differenced VI) is rather limited. This applies to biomass estimation in arid to semi-arid regions using optical data with low resolution (> 1 km) (Brandt et al. 2014, Diouf and Lambin 2001, Holm et al. 2003, Kawamura et al. 2005, Tucker et al. 1985, Wessels et al. 2006, Xu et al. 2013) and medium resolution (> 5 m - < 1 km) (Aranha et al. 2008, Kraus and Samimi 2002, Qi and Wallace 2002, Samimi 2003, Samimi and Kraus 2004, Wiley et al. 2002).

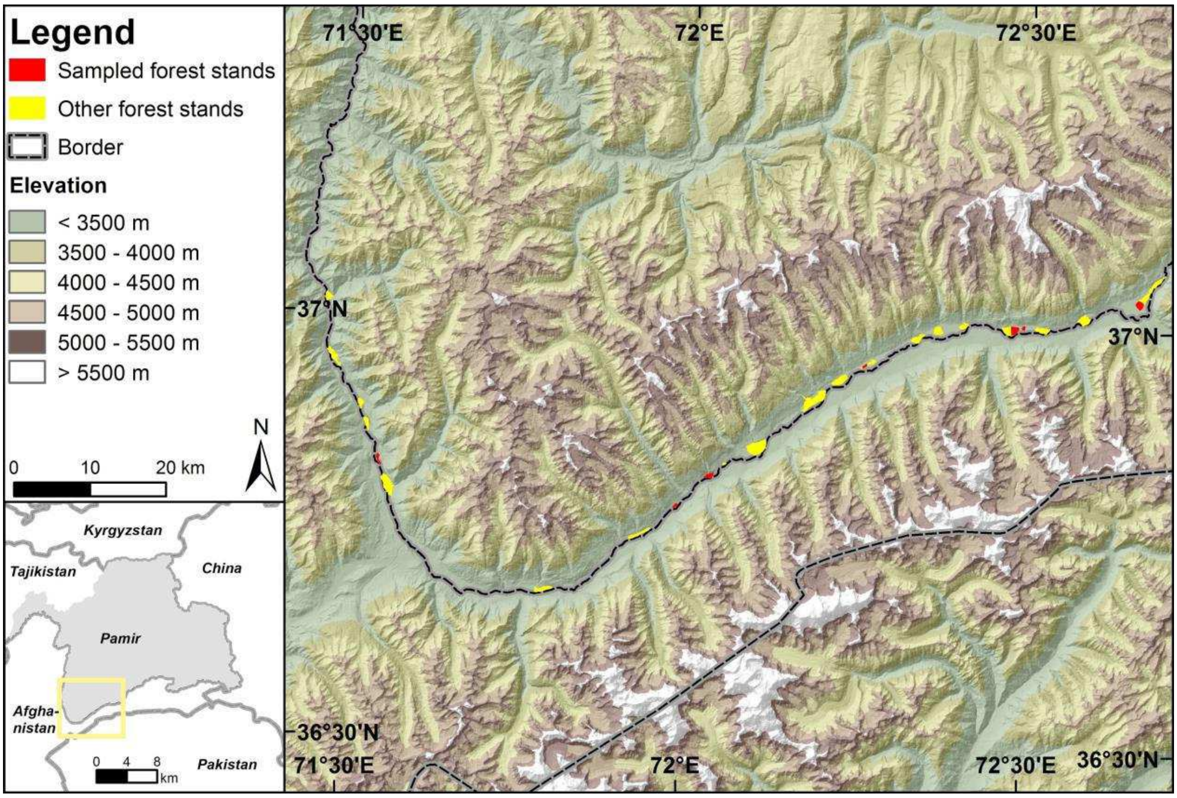
To overcome this methodological barrier and to find proxies which could improve the accuracy in retrieving biomass information in sparsely vegetated areas, different techniques and sensors have been used and tested, also given the availability of high-resolution satellite data in combination with multi- or hyperspectral information (Eisfelder et al. 2012, Eitel et al. 2011, Zandler et al. 2015 a, b). Nonetheless, clear recommendations on the suitability of specific sensors for semi-arid to arid environments are lacking and the development of an operational technique that is consistently accurate and reproducible still remains challenging until today (Eisfelder et al. 2012, Qi and Wallace 2002).

Synthesizing suggestions, the red edge band (spectral range between 690-730 nm) is supposed to be more effective in differentiating the reflectance of the soil background from woody reflectance characteristics due to its wavelength position at the edge between red and near infrared (690-730 nm) (Clevers et al. 2002). Thus red edge indices could favor biomass estimation in semi-arid landscapes more than traditional VIs (Brantley et al. 2011, Eisfelder et al. 2012, Eitel et al. 2011, Vanselow and Samimi 2014). Besides the use of red edge indices, it is suggested to include also texture attributes of satellite images (Attarchi and Gloaguen 2014, Eckert 2012, Kelsey and Neff 2014, Lu 2005, 2006, Sarker and Nichol 2011, Vanselow and Samimi 2014, Zandler et al. 2015a). Image texture discriminates spatial variability of neighboring pixels independent from image tone (Luckman et al. 1997). The review of existing scientific literature has shown that little research has been conducted and published on woody biomass estimation in semi-arid regions using high resolution imagery in combination with indices including the red edge band or texture attributes. The main objective of this study is therefore to improve the understanding of the interrelationship between multispectral high-resolution satellite data and ground-measured woody biomass in semi-arid ecosystems with scarce woody vegetation. Our hypothesis is that red edge indices in combination with texture attributes are more effective for woody biomass estimation than conventional broadband spectral information. The hypothesis is tested by linking high-resolution RapidEye satellite data with obtained field data of woody biomass volume in a semi-arid high mountainous region in Tajikistan.

2. Study area

Sampled forest plots for obtaining field measurements of woody biomass are located in a valley in the southwestern part of Gorno Badakhshan Autonomous Oblast (also known as the Tajik Pamirs) in the eastern high mountains of Tajikistan (Fig. 1). In this region, the local energy demand for cooking and heating is high, because of a long heating season of up to six months (Wiedemann et al. 2012, Mislimshoeva et al. 2014). Woody biomass, used as firewood, is of major importance to cover the energy needs of the local population (Mislimshoeva et al. 2014). However, due to the mountainous topography and a continental climate with long winters and considerable dryness, habitats for woody biomass are scarce (Breu et al. 2005, Hoeck et al. 2007). Only fertile riparian zones and alluvial fans can provide larger habitats for denser woody vegetation (Breckle and Wucherer 2006, Vanselow et al. 2015). However, these fertile areas are also important for crop cultivation and livestock farming, implying a competitive situation in benefiting from different ecosystem services on a small scale (Schumacher 2014). Given the importance of the availability of firewood for the local population and the lack of related research, there is a strong necessity to obtain information on forest woody biomass stocks.

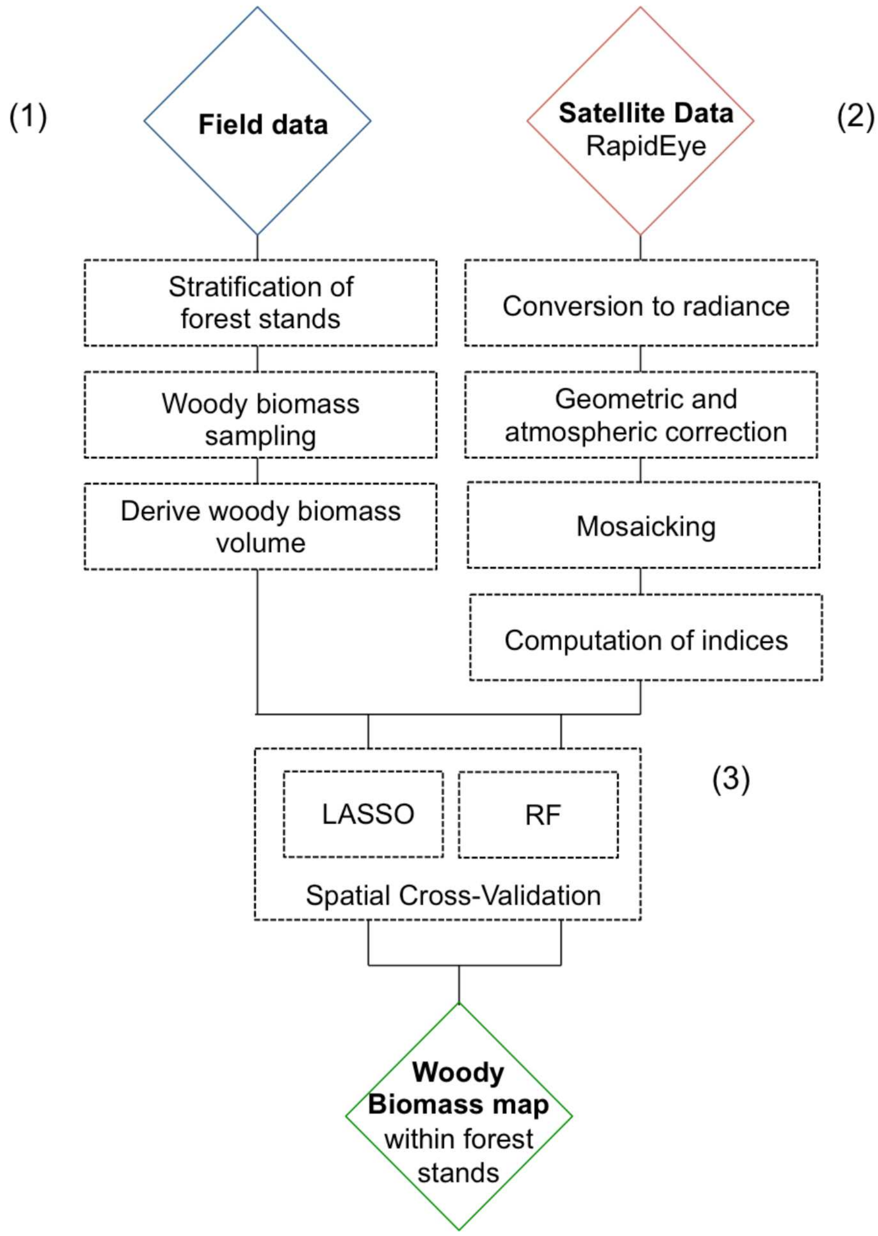
Figure 1. Overview map of research area and sampled forest plots.



3. Methods

The methodological approach of the study included three steps shown in Figure 2: (1) Obtaining ground measured woody biomass information and derive woody biomass volume, (2) processing of satellite images including the development of indices and (3) linking both ground and satellite based data sources to find a correlation and spatially predict woody biomass volume for sampled forest plots.

Figure 2. Flowchart of forest woody biomass volume estimation model



3.1. Field Data

Field data were collected in August and beginning of September 2013 in seven forest stands distributed along the valley (Fig. 1). These forest stands are found inside defined plots according to the cadaster and serve as source of firewood and timber for the adjacent villages. Demarcation and size of the plots are defined by the cadaster. To homogeneously distribute sampling transects in relation to size and vegetation density of the stands, a pre-stratification of the stands was conducted. Four vegetation cover classes were defined within the forest stands (Fig. 3) based on very high resolution Google Earth Images from 2008, a land cover map based on QuickBird imagery from 2008 (GTZ 2009), and a guided walk through the whole forest stand with local foresters (purposive sampling). The guided walk, considered as purposive sampling, was conducted to update the pre-stratification of the stands, as timely corresponding satellite images were not available prior to the time of field data collection.

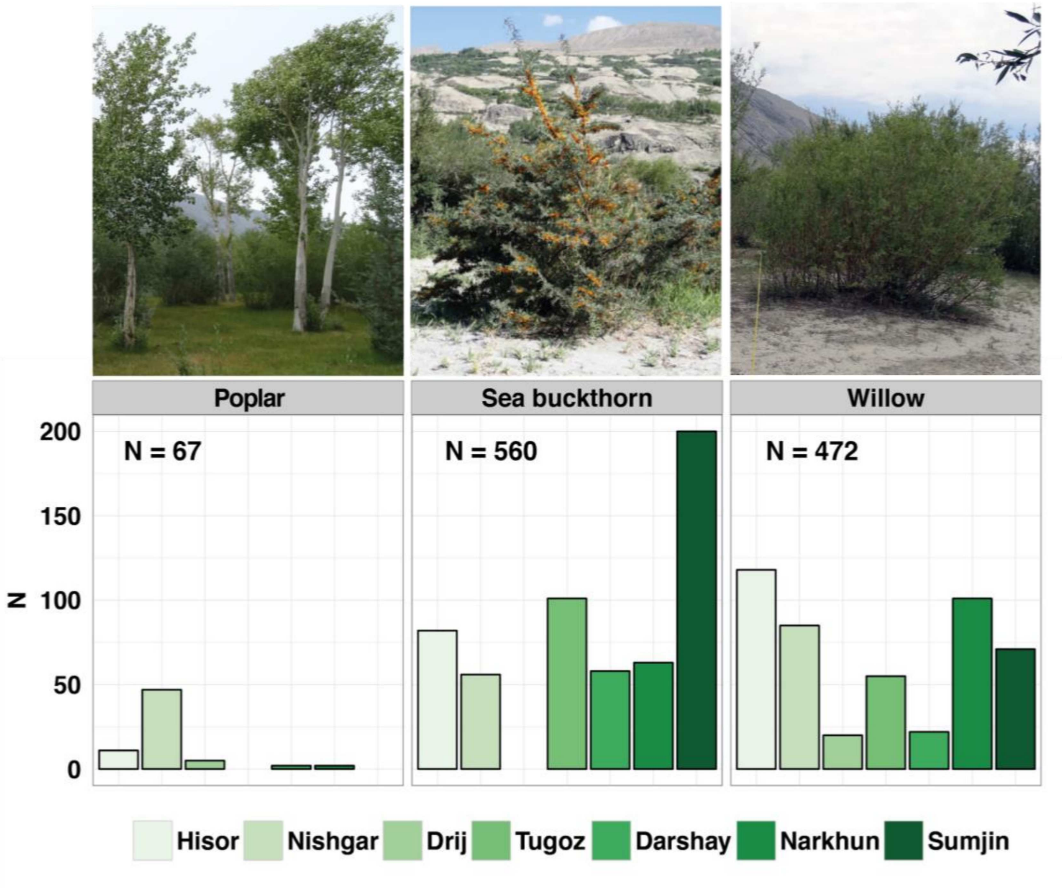
Figure 3. Assigned vegetation cover classes according to stratification of forest stands in the research area

Based on the pre-stratification, overall 95 sampling transects were placed in the different assigned class. Data collection in each sampling transect followed the Line Intercept Method (Canfield 1941, cited in Mueller-Dombois and Ellenberg 1974). This method is especially feasible when field measurements over a larger area are required (Mueller-Dombois and Ellenberg 1974, McCoy 2005) and when boundaries of plant growth are relatively easy to determine as for semi-arid shrubby vegetation types (Coulloudon et al. 1999). Each sampling transect represented a 20 x 2 m transect. Within each transect quantitative data of each individual standing tree and shrub was recorded.

3.1.1. Sampled Woody Species

The small-leaved mountain forest, also known as riparian or floodplain forest (Akhmadov 2008, GTZ 2010), is predominant in the region, and consists of the following main species: willow species (*Salix turanica, Salix shugnanica, Salix wilhelmsiana, Salix alba),* poplar species *(Populus pyramidalis, Populus pamirica*) and sea buckthorn (*Hippophae rhamnoides*) (Akhmadov 2005, 2008, Akhmadov et al. 2005, GTZ 2010). All sampled transects were dominated by willow (*Salix spec.*) (*N* = 472) and sea buckthorn (*H. rhamnoides*) (*N* = 560), whereas poplars (*Popolus spec.*) (*N* = 67) were only present on some plots in smaller abundance (Fig. 4).

Figure 4. Sampled species: poplars *(Popolus spec.),* willow *(Salix spec.),* sea buckthorn *(Hippophae rhamnoides)* with respective distribution of measured individuals per species over all sampled transects per forest stand.



3.1.2. Field measurements and woody biomass volume calculation

Field measurements in the sampling transects were non-destructive. Constraints in time and absent permission to conduct extensive destructive measurements in the study region made it not possible to develop more reliable allometric functions. Therefore, in this case woody biomass volume was derived from non-destructive measurements including:

(1) Most common dimensions (stem diameter and height) to determine the stem volume of a standing tree or shrub consisting of stem plus bark, which is widely considered as merchantable stem and bark biomass (Cannell 1984, Gray 1956, Hoyer 1985, Jenkins et al. 2004). Stem volume was estimated as a function of stem basal area, derived from diameter or circumference, and height (Hoyer 1985). Circumference was measured with a measuring tape at breast height ($d_{1.3m}$) for single stemmed trees, whereas for multiple stemmed shrubs the diameter of each single stem sprouting from the ground was determined with a caliper at knee height ($d_{0.3m}$) and summed up. Total height (h_{tot}) was measured for single stemmed trees and average height (h_{avg}) for multiple stemmed shrubs with a clinometer. As Hoyer (1985) in his formula does not consider the shape of a stem or branch, a form factor approximately representing the shape of a stem was integrated to increase accuracy (Bebarta 2011, Canfield 1941 in Mueller-Dombois and Ellenberg 1974, Laar and Akca 2007). This factor again has not been derived from empirical destructive measurements, but also on site from measurements at the standing tree or shrub. For the artificial form factor (f), diameters of a standing stem at knee height ($d_{0.3m}$) and breast height ($d_{1.3m}$) were measured. Subsequently, the ratio from these two values was derived to gain an approximate factor for the taper shape. The form factor was calculated on the basis of 100 willow and sea buckthorn individuals respectively as well as of 35 poplar individuals. Integrating all parameters, equations for single stemmed trees (V_{tree}) and for multiple stemmed shrubs (V_{shrub}) are as follows [EQ 1, 2]. The calculated biomass volume per individual was summed up for the whole transect and thus served as input data for the statistical regression with satellite data.

$$V_{tree} = \frac{\pi}{4} * (d_{1.3m})^2 * h_{tot} * f \qquad \text{EQ (1)}$$

$$V_{shrub} = \frac{\pi}{4} * (\sum_{i=0}^{n} * d_{0.3m})^2 * h_{avg} * f \qquad \text{EQ (2)}$$

(2) Besides information for biomass volume, measurements of crown diameter over two lengths (shortest and longest) were recorded to determine the projected crown area. This

additional parameter is very important, because foliage biomass was not considered in the volume calculations. During time of fieldwork and acquisition dates of the satellite imagery, phenology of measured species had its peak, signifying the annual maximum of foliage production. To legitimize a correlation between woody biomass and remote sensing signals focusing on the green vegetation structure, a strong relationship between measured stem volume and projected crown area is required.

3.2. Satellite Data

High-resolution RapidEye satellite images (8 tiles; 25 x 25 km each) were obtained from the RapidEye Science Archive with a pixel spacing of 6.5 m, resampled to 5 m. The acquisition dates of the images were chronologically very close (2013-07-13; 2013-07-19) and close to the dates of the fieldwork enabling a comparison with the field measurements.

Image data were atmospherically corrected using the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) module in ENVI version 4.7 (see Spiekermann et al. 2014, Zandler et al. 2015a). As further steps, images were geographically corrected using field based GPS reference points, as well as mosaicked using a feathering algorithm.

To exploit spectral and spatial information for computing indices, mean reflectance values of each band were extracted for the pixels covered by the sampling transects. Various indices were calculated with the derived reflectance values (Table 1). The indices can be categorized in (i) Single Bands, representing reflectance values within the spectral range; (ii) Band Ratios, which detect differences in surface properties; (iii) Broadband Greenness VIs, measuring photosynthetic activity (Tucker 1979); (iv) Red edge indices, which use reflectance measurements in narrow red edge reflectance portion, showing maximum sensitivity for detecting the state of the vegetation (Verrelst et al. 2006); (v) Soil Adjusted VIs, which attempt to minimize the effect of soil background (Gilabert et al. 2002); and (vi) Leaf Pigments VIs, which do not measure chlorophyll but stress-related pigments present in vegetation (Verrelst et al. 2006). Besides spectral information, spatial information was extracted from the satellite data. A co-occurrence-based filter was used to extract the following image texture parameters: mean, variance, homogeneity, contrast, dissimilarity, entropy, second moment and correlation (Haralick et al. 1973). The filter window size was kept low (3 x 3 pixels), in order not to lose spatial information due to over-smoothing of textural variations.

Table 1. Categorized indices used in this study (selected)

Indices	Description/Equations	References
Single Bands	***Represent reflectance values within respective spectral range*** B1 - - B5	
Band Ratios	***Detect spectral differences and thus differences in surface properties*** B1/B2 - - B1/B5; B2/B3 - - B2/B5; B3/B4 - - B3/B5; B4/B5	
Broadband Greenness VIs	***Try to measure and display the overall amount of photosynthetic material in vegetation***	Tucker 1979
Chlorophyll Index Green/ Chlorophyll Green Model	$CGM = \frac{NIR}{G} - 1$	Gitelson et al. 2005
Green Normalized Difference Vegetation Index	$GNDVI = \frac{NIR-G}{NIR+G}$	Gitelson & Merzylak 1997, Loris & Damiano 2006
Green Blue Normalized Difference Vegetation Index	$GBNDVI = \frac{NIR-(G+B)}{NIR+(G+B)}$	Wang et al. 2007
Normalized Difference Vegetation Index	$NDVI = \frac{NIR-R}{NIR+R}$	Rouse et al. 1974, Tucker 1979
Red edge indices	***Use reflectance measurements in red edge reflectance portion; show maximum sensitivity for detecting state of vegetation.***	Verrelst et al. 2006
Browning Reflectance Index	$BRI = \frac{\frac{1}{G}-\frac{1}{RE}}{NIR}$	Merzylak et al. 2003
Canopy Chlorophyll Content Index	$CCCI = \frac{\frac{NIR-RE}{NIR+RE}}{\frac{NIR-R}{NIR+R}}$	Barnes et al. 2000
Normalized Difference Near-Infrared Red Edge	$NDRE = \frac{NIR-RE}{NIR+RE}$	Barnes et al. 2000, Gitelson & Merzylak 1994
Normalized Difference Red Edge Red	$NDRE = \frac{RE-R}{RE+R}$	
Tasseled Cap – Soil Brightness Index	$TCSBI = 0.332*G + 0.603*R + 0.675*RE - 0.262*NIR$	Kauth & Thomas 1976, Bannari et al. 1995
Soil Adjusted VIs	***Attempt to minimize the effect of soil background as one source of variation by integrating soil-adjustment parameters***	Gilabert et al. 2002
Enhanced Vegetation Index	$EVI = \frac{2.5*NIR-R}{NIR+6*R-7.5*B+1}$	Huete et al. 1997
Soil Adjusted Vegetation Index	$SAVI = \frac{NIR-R}{NIR+R+0.5} * (1+0.5)$	Huete 1988
Leaf Pigments	***Do not measure chlorophyll, but stress-related pigments present in vegetation***	Verrelst et al. 2006
Anthocyanin Reflectance Index	$ARI = \frac{1}{G} - \frac{1}{RE}$	Gitelson et al. 2009
Texture Information	***Detect structural details of surface***	Haralick et al. 1973
Single Bands	TB1 - - TB5	
Band Ratios	TB1/TB2 - - TB1/TB5; TB2/TB3 - - TB2/TB5; TB3/TB4 - - TB3/TB5; TB4/TB5	

B1 - - B5: Band 1 - - Band 5, NIR: Near-Infrared, RE: Red Edge, R: Red, G: Green, B: Blue, TB1 - - TB5: Texture of Single Band 1 - - 5

3.3. Modeling woody biomass

The large number of potential predictors (160) exceeds number of ground observations (95), which creates a high-dimensional problem and may lead to overfitting of models (James et al. 2013). To prevent this issue, two different models were selected, which are stated to be effective in this context. Firstly, a linear model with variable selection based on the LASSO (Least Absolute Shrinkage and Selection Operator) technique was chosen as a method that uses shrinkage heuristics and performs variable subset selection prior to prediction (Zandler et al. 2015a). Thus, this method is able to deal with large numbers of variables and it is also robust regarding unequally distributed variables (Hastie et al. 2009). An internal cross-validation was used to optimize the shrinkage penalty. Secondly, the Random Forest (RF) technique was used, which has become quite popular in remote sensing applications when dealing with high-dimensional data (Pal 2005). This technique is based on a large number of decision trees (in this study, 500) fitted to random subsets of the training sample. Both LASSO and RF were fitted to logarithmic (to the base 10) woody biomass data to better account for non-negativity and nonlinearity. One outlier value in four predictors was trimmed to a value near the second most extreme observed value in the sample.

Predictive model performances of LASSO and RF were estimated using spatial cross-validation (Brenning, 2012). Considering the spatial clustering of field sites and expected autocorrelation of observations within forest stands, the data set was subdivided into 5 spatial subsets containing between 9 and 29 observations. Fivefold cross-validation was performed using this partitioning. Thus, one subset at a time was used as a test set, while the other four were used as training set for a predictive model (James et al. 2013). Predictions from all five test sets were combined in order to calculate cross-validation bias, standard deviation and Root Mean Square Error (RMSE) at the logarithmic and non-logarithmic scale of woody biomass. In addition, three different predictor sets of indices (1: predictor set with only broadband VIs including single bands and band ratios; 2: predictor set 1 + red edge indices; 3: predictor set 1 + 2 + texture attributes) were fed into the model to assess importance of red edge indices and texture attributes. Topographic information (e.g. Digital Elevation Model) was not integrated as sampled forest stands were located only in flat riparian zones.

One model was selected based on model performance and computational complexity in order to map the woody biomass volume for all sampled forest stands in the study region. In order to assess each predictor's relative predictive importance, the permutation-based approach was used (see Strobl et al. 2007, Brenning 2012). Specifically, each predictor was randomly permutated in order to obtain degraded predictions on spatial cross-validation test sets, and the increase in cross-validation RMSE was used as a measure of variable importance. In the case of the LASSO model, linear model coefficients were furthermore extracted as indicators of variable selection and importance. Nevertheless, variable importance measures in this high-dimensional setting should be taken with a grain of salt due to the high degree of redundancy in the data. For example, without even considering collinearity among multiple predictors, 25% of all pairwise Pearson's correlations among predictors were > 0.80 in absolute value.

Statistical calculations were implemented with R, using Packages 'glmnet' for LASSO (Friedmann et al. 2010), 'randomForest' for Random Forest (Liaw & Wiener 2014), 'sperrorest' for spatial cross validation and variable importance (Brenning 2012), and 'RSAGA' for spatial prediction on raster stacks (Brenning 2013).

4. Results

4.1. Ground measured and calculated parameters

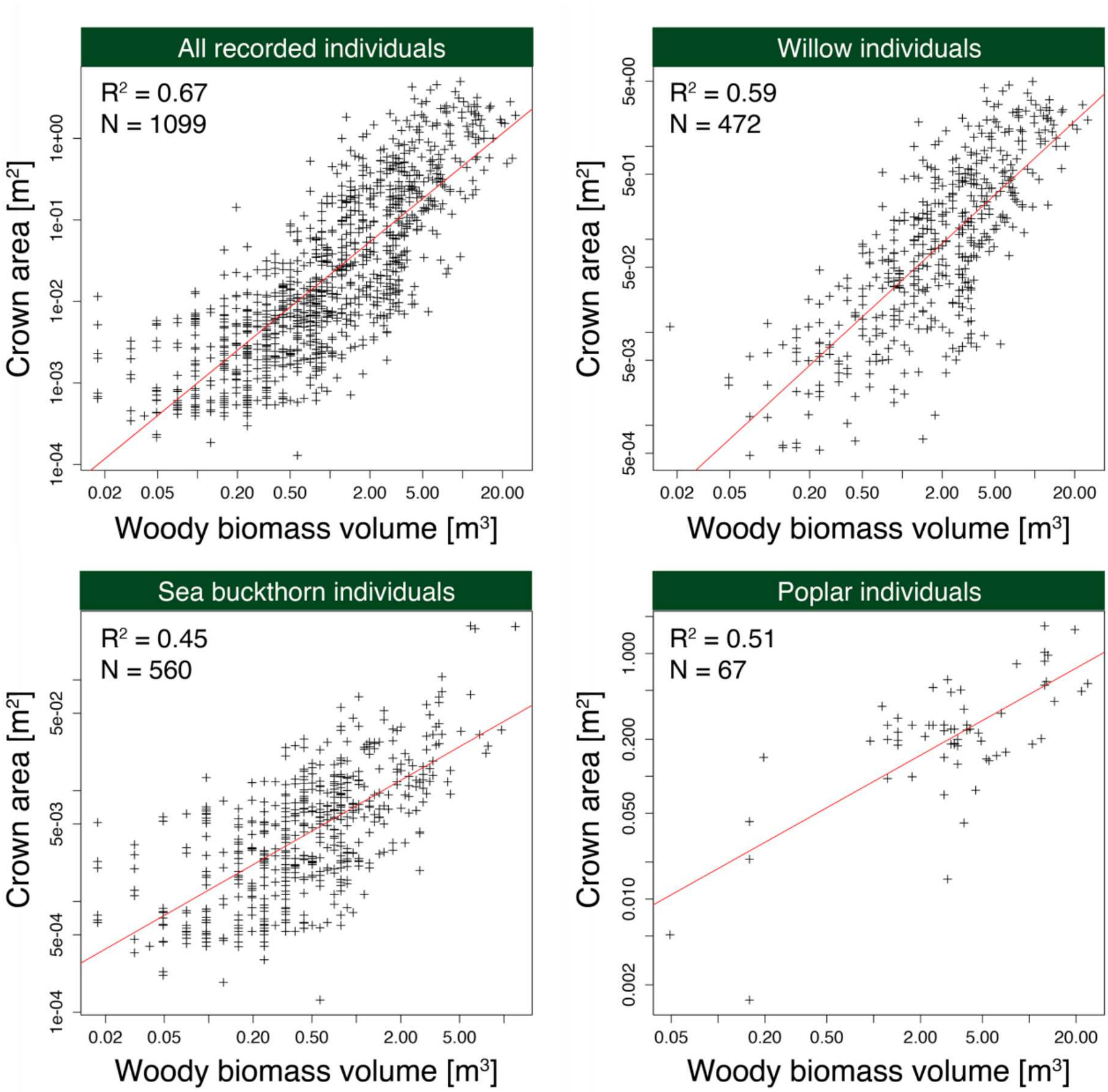
Focusing on height and diameter as main input variables for estimating woody biomass, poplars were the highest individuals measured, whereas sea buckthorn individuals were relatively small. Willow individuals had a high abundance of stems sprouting from the ground leading to high values for diameter. Poplars had primarily single solid stems. Diameter values for sea buckthorn individuals were rather low. In comparison to willow, the stems were relatively small. Crown area was biggest for poplar and willow individuals.

Woody biomass volume was calculated for each recorded individual. Poplars and willows had similar biomass values, whereas the span between minimum and maximum biomass values was much larger for willows. For poplars, height of the single stems was the decisive factor for biomass values. Willow individuals do not grow very high, but due to a high abundance of stems the woody biomass volume was similar to the one of poplars. Sea buckthorn individuals showed the lowest values for woody biomass volume. Even though the individuals often appear rather bulky, the actual woody biomass was comparatively low.

4.2. Correlation between woody biomass volume and crown area

According to the correlation analysis between measured crown area and calculated woody biomass volume over all individuals, a moderately strong relationship of r^2=0.67 exists (Fig 5). Looking at correlations for single species the correlation is lower. The lowest correlation was found for sea buckthorn (r^2=0.45). With consideration of included uncertainties, this correlation legitimizes a direct statistical linkage of calculated woody biomass with spectral reflectance, mainly measuring vegetation greenness.

Figure 5. Relationship between crown area and calculated woody biomass volume over all individuals and per species



4.3. Empirical biomass models and variable importance

LASSO and RF both achieved only rather limited performances in woody biomass prediction. This is true for all predictor sets of VIs (Table 4). The model performances for both LASSO and

RF increase with feeding red edge indices (predictor set 2) into the model, but show the best performances with adding both, red edge indices and texture attributes (predictor set 3).

Table 4. Summary statistics of cross-validated LASSO and RF model results for different predictor sets

	Predictor set 1	Predictor set 2	Predictor set 3
LASSO			
Bias	1.06	1.07	0.89
Standard Dev.	2.69	2.69	2.69
RMSE	2.98	2.94	2.75
Correlation	0.12 (PC)	0.13 (PC)	0.31 (PC)
Obs/Pred	0.33 (SC)	0.26 (SC)	0.51 (SC)
	Log-scale		
Bias	0.03	0.02	-0.02
Standard Dev.	0.81	0.81	0.81
RMSE	0.76	0.78	0.71
Correlation	0.40 (PC)	0.37 (PC)	0.52 (PC)
Obs/Pred	0.33 (SC)	0.26 (SC)	0.51 (SC)
Random Forest			
Bias	0.88	0.83	1.06
Standard Dev.	2.69	2.69	2.69
RMSE	2.87	2.80	2.67
Correlation	0.20 (PC)	0.25 (PC)	0.40 (PC)
Obs/Pred	0.33 (SC)	0.37 (SC)	0.50 (SC)
	Log-scale		
Bias	0.02	-0.007	0.001
Standard Dev.	0.81	0.81	0.81
RMSE	0.77	0.76	0.70
Correlation	0.40 (PC)	0.43 (PC)	0.51 (PC)
Obs/Pred	0.33 (SC)	0.37 (SC)	0.50 (SC)

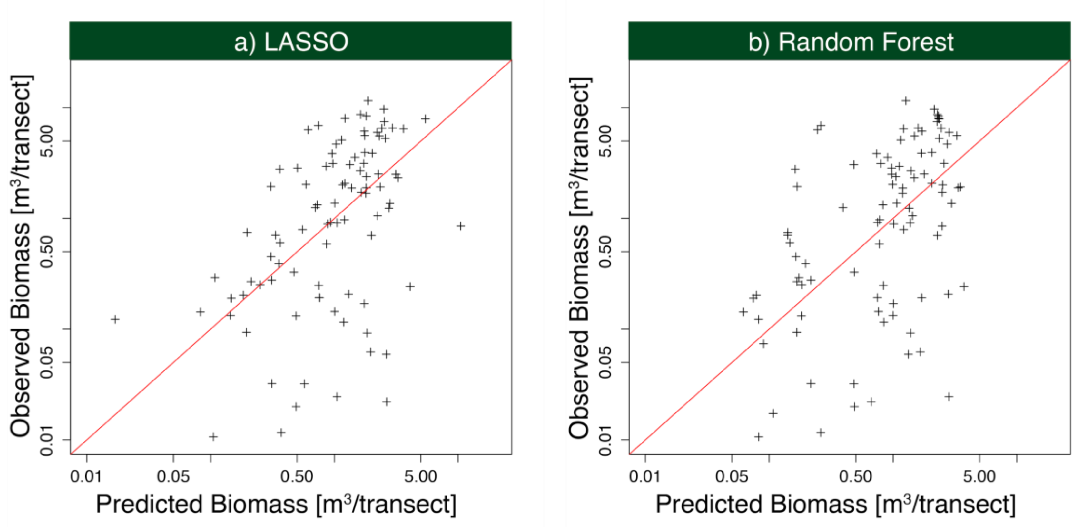
Predictor Set 1 = Single Band + Band Ratio + Soil Adjusted VIs + Leaf Pigments VIs + Broadband VIs; Predictor Set 2 = Predictor Set 1 + Red edge VIs; Predictor Set 3 = Predictor Set 1 + Predictor Set 2 + Texture attributes; PC: Pearson - Correlation; SC: Spearman - Correlation

The best models, using predictor set 3 as input data, show Spearman's correlations of 0.51 for LASSO and 0.50 for RF, respectively, between measured values and predictions on cross-validated test sets. Logarithmic-scale cross-validated RMSEs of 0.71 (LASSO) and 0.70 (RF) showed some predictive skill considering an overall standard deviation of logarithmic woody biomass of 0.81. High values of RMSE at the non-logarithmic scale (LASSO: 2.75 m^3; RF: 2.69 m^3) may seem disappointing compared to the woody biomass standard deviation of 2.69 m^3; however, these values are inflated by extreme values especially in the case of the less robust LASSO method as a linear model. The mentioned Spearman correlations and the somewhat lower Pearson's correlations of 0.31 (LASSO) and 0.40 (RF) confirm the influence of outliers and the (limited) predictive capability (*p*-values <0.01 for both correlation tests).

Among the top 20 predictors in the permutation-based assessment for RF were nine texture attributes, eight red-edge indices and three band ratios, also including the red edge band. Considering the most important variables for the sparser LASSO models, particularly important were four texture attributes, four red-edge indices, and one band ratio of red edge and green bands (only eleven for LASSO because predictors ranked lower than the top eleven show substantially lower variable importance values).

Scatterplots of predicted versus observed woody biomass for both better performing models, LASSO and RF, show that predicted values are rather lower than observed values (Fig 6).

Figure 6. Scatterplots of predicted versus observed woody biomass in m^3/transect for best performing model a) LASSO and b) Random Forest



The biomass map, obtained with the best performing model (LASSO: Predictor set 3; Log-Scale; PC = 0.52; RMSE = 0.71), generally predicted low values between 20 and 60 m^3 of woody biomass volume per ha (Fig. 7). Woody biomass is mainly scattered over the plots, tending to decrease to the edges of the plots, and to increase along small canals (e.g. Hisor, where small canals meander through the forest plot) and other water sources such as gorges (e.g. Narkhun). Only for *Tugoz* predicted biomass can be found homogeneously over the whole plot. This distribution corresponds with the observations in the field. On the forest plot in Tugoz the highest average stock of woody biomass per hectare can be found (56.6 m^3 ha^{-1} of woody biomass). For the other plots woody biomass ranges between 25 and 40 m^3 ha^{-1} (Table 5). However, absolute values shall be interpreted with caution.

Figure 7. Predicted woody biomass map in m³ ha⁻¹ for each forest stand with LASSO (Predictor set 3; Log-Scale; PC = 0.52; RMSE = 0.71)

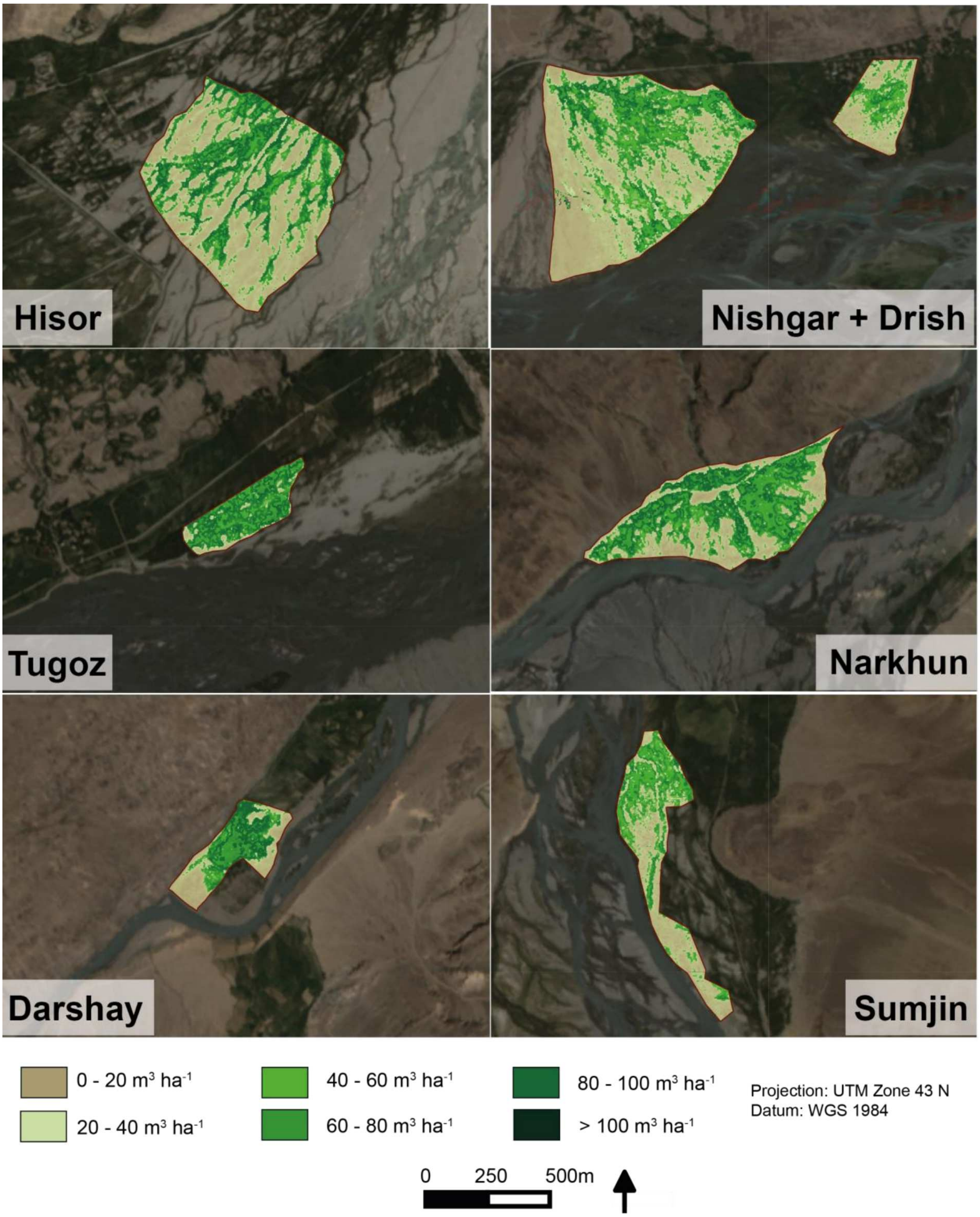


Table 5. Distribution of predicted woody biomass volume for each sampled forest plot

	Hisor	Nishgar	Drij	Tugoz	Narkhun	Darshay	Sumjin
Plot size [ha]	71.7	74.9	12.6	12.5	44.7	14.0	24.2
Stock [m3/ha]	30.8	40.8	24.4	56.6	41.2	41.8	28.7
Stock [m3/plot]	2211.3	3052.5	308.0	707.7	1839.8	584.8	695.5

5. Discussion

5.1. Model performance

In this study high-resolution red edge and texture features retrieved from RapidEye satellite images were used to tackle the challenge of remote sensing based woody biomass estimation in semi-arid regions. We demonstrate that red edge indices and texture attributes improve the predictive performance in comparison to focusing only on conventional broadband VIs. In this respect our findings are consistent with several other studies (Ali et al. 2015, Eitel et al. 2011, Kross et al. 2015, Li et al. 2012). However, many studies testing red edge indices focus either on regions with high biomass levels or on crops. For example, in Eitel et al. (2011), red edge information improved the detection of stress related shifts in foliar chlorophyll in conifer woodland. Ali et al. (2015) tested the red edge band for estimating winter wheat and found a better correlation of red edge indices with the Leaf Area Index of winter wheat than with conventional VIs. Kross et al. (2015) found similar results estimating biomass in corn and soybean crops.

Findings for woody biomass estimation testing red edge indices particularly in semi-arid to arid regions are diverse. In Li et al. (2012) the red edge VI outperformed commonly used NDVI in estimating vegetation fraction in arid regions. For savanna (Ramoleo et al. 2012), desert steppe (Ren et al. 2011), and grass/herb vegetation (Cho and Skidmore 2009) the analyses showed similar results. In other studies, however, the additional red edge band was not superior to other model inputs (Vanselow and Samimi 2014, Zandler et al. 2015a). Here, SAV (Spectral Angle Values) based variables, Soil Adjusted Vegetation Indices or topographic variables were more important.

For texture measures the study landscape looks similar. The general picture of the studies is in line with our findings. Texture measures play an important role in predicting biomass. In Fuchs et al. (2009), Kesley and Neff (2014), and Sarker and Nichol (2011) for example, texture variables distinctively improved forest biomass estimates and carbon prediction, however, again in biomass rich areas. Eckert (2012) found in her study that biomass correlates more with texture measures than with conventional spectral parameters, especially in degraded forest areas. In strongly arid regions, texture measures were also found as important variables (Vanselow and Samimi 2014, Zandler et al. 2015), but not as decisive as in other studies. In these two studies it is also suggested to further exploit texture variables not only from single bands, but also from indices, such as soil adjusted indices. This showed an improvement of the model performance in Vanselow and Samimi (2014).

5.2. Model uncertainties

Even though the predictive capacity of the model increased with red edge indices and texture attributes, the overall model accuracy was still rather moderate. Uncertainties, therefore, need to be taken into consideration when looking at the predicted biomass distribution map (for practical use). High Predictive errors above 50% can also be found in other studies that relate biomass in semi-arid regions to optical remote sensing data (Aranha et al. 2008, Holm et al. 2003, Powell et al. 2010, Zandler et al. 2015), whereas a direct comparison of statistical results has to be treated with caution.

Predictive uncertainty can partly be attributed to the fact that especially in semi-arid landscapes where sparse and woody vegetation is predominant, the photosynthetic signal captured by most spectral bands and indices is biased. Pixels are mixed partially with a strong soil background or herbaceous vegetation and plants consisting of photosynthetic and nonphotosynthetic woody material. A multi-temporal approach trying to map soil, herb, shrub and tree cover according to seasonal phenological differences may be appropriate to tackle this issue as suggested and successfully implemented in Shoshany and Svoray (2002). In addition, hyperspectral satellite data may reduce model uncertainties for satellite-based vegetation analysis in drylands, as the higher spectral resolution is more capable in capturing the non-photosynthetic part of wood plants (Zandler et al. 2015b). Furthermore, uncertainties regarding field observations need to be considered. On the acquisition dates of the satellite imagery (mid to end of July) foliage biomass was present because of the peak of the vegetation period. In contrast, only woody biomass excluding foliage biomass was measured on the ground. Therefore the correlation between measured biomass and remote sensing signals was only moderately strong (Fig. 5). This indicates weaknesses in the direct statistical linkage of ground-measured biomass with satellite data.

A few limitations with respect to woody biomass volume calculation need to be noted. Destructive harvesting techniques or allometric equations (Sah et al. 2004) were challenging to apply in this study, given the available time frame and official permission for collecting field data. In addition, allometric equations, which could be used in such a case, do not exist for the research area. Transferability of allometric equations from other regions is due to the site and species specificity rather challenging and thus not applicable in this context. To further increase accuracy of the chosen equations, an artificial form factor, which represents the shape of the stem, was included. The derived artificial form factor (for poplar and sea buckthorn 0.73; for willow 0.69) is similar to other studies. According to Cannell (1984), empirical studies on 640 forest and woodland stands around the world found out that heavily branched stands had form factors in the range of 0.6 - 0.8. This underlines the fact that the derived artificial form factor represents a solid reference value for the stem shape. Still, the mentioned uncertainties regarding ground-based measurements indicate the tradeoff between gaining accurate measurements and having a less labor and time intensive method.

5.2. Statistical performance and importance of predictors

The challenge of having a large number of predictors was tackled with choosing LASSO using an integrated shrinkage technique, and the tree based RF model. For both models the suitability in such a high-dimensional setting was proven in different studies. In the case of LASSO, Lazaridis et al. (2011) and Zandler et al. (2015a) tested shrinkage regression techniques in comparison to other standard methods and came to the conclusion that LASSO performed particularly well. According to cross-validated model performances, RF model produced similar results to LASSO. This is contrary to Zandler et al. (2015a), where RF model performed poorer than most other models. However, in Powell et al. (2010) lowest RMSE was produced with RF for forest biomass estimation.

In the context of variable importance, red edge indices and texture attributes are highly dominant among the top predictors. However, the significance of the variable importance has to be considered carefully in such a high dimensional setting. Additionally, collinearity was not considered when feeding in additional predictors.

6. Conclusion

In summary it can be stated that this research further improved the understanding of estimating woody biomass in a semi-arid ecosystems with scarce vegetation using high-resolution multispectral satellite data. Many studies using optical satellite data tested the suitability of red edge and texture measures for crop and grass vegetation or in areas with high biomass levels. Knowledge about its potential for woody and shrubby vegetation in a strongly semi-arid to arid context is still limited. Our study showed that red edge indices and texture measures play an important role in woody biomass estimation as the model performance significantly improved in direct comparison to conventional VIs. Still, as our achieved model performance highlights, biomass mapping in these environments is subject to further improvements.

As research outlook, it is suggested to focus on high-resolution hyperspectral data to achieve better model performance for woody biomass estimation in semi-arid areas. Studies already showed suitability in arid environments. Furthermore, airborne (including unmanned) laser scanning could be utilized depending on the scale of assessment. It is very accurate in assessing forest characteristics such as stand height or distribution of biomass volume and can generate better training data for the correlation with satellite data. From a field methodological point of view it may be useful to increase the number of sampling points or develop allometric functions for local woody species to increase accuracy of ground data.

Acknowledgments

We would like to express our gratitude to the Deutsche Zentrum für Luft- und Raumfahrt (DLR) for the data provision from the RapidEye Science Archive and to the Alexander von Humboldt Foundation for funding the field trip of Paul Schumacher to the research area to collect field data. Furthermore we thank the reviewers for their constructive comments to improve the manuscript.

References

Akhmadov, K. *Forest and forest products country profile: Tajikistan, Geneva Timber and Forest Discussion Paper 46*. (2008).

Akhmadov, K. Country statement Tajikistan - Forest Resources Assessment for Sustainable Forest Management. in *Capacit. Build. Shar. For. Mark. Inf.* 6 (2005).

Akhmadov, K. M., Breckle, S.-W. & Breckle, U. in *L. Use Chang. Mt. Biodivers.* 241–250 (2005).

Ali, M. *et al.* Estimation and Validation of RapidEye-Based Time-Series of Leaf Area Index for Winter Wheat in the Rur Catchment (Germany). *Remote Sens.* **7,** 2808–2831 (2015).

Aranha, J. T., Viana, H. F. & Rodrigues, R. Vegetation Classification and quantification by satellite image processing. A case study in North Portugal. in *Bioenergy Challenges Oppor. - Int. Conf. Exhib. Bioenergy* **3,** (2008).

Asner, G. P., Wessman, C. A., Bateson, C. A. & Privette, J. L. Impact of Tissue , Canopy , and Landscape Factors on the Hyperspectral Reflectance Variability of Arid Ecosystems. *Remote Sens. Environ.* **74,** 69–84 (2000).

Asner, G. P. *et al.* Forest Canopy Gap Distributions in the Southern Peruvian Amazon. *PLoS One* **8** (2013).

Attarchi, S. & Gloaguen, R. Improving the estimation of above ground biomass using dual polarimetric PALSAR and ETM+ data in the Hyrcanian mountain forest (Iran). *Remote Sens.* **6,** 3693–3715 (2014).

Avitabile, V., Baccini, A., Friedl, M. a. & Schmullius, C. Capabilities and limitations of Landsat and land cover data for aboveground woody biomass estimation of Uganda. *Remote Sens. Environ.* **117,** 366–380 (2012).

Ayanu, Y. Z., Conrad, C., Nauss, T., Wegmann, M. & Koellner, T. Quantifying and mapping ecosystem services supplies and demands: a review of remote sensing applications. *Environ. Sci. Technol.* **46,** 8529–41 (2012).

Bannari, A., Morin, D., Bonn, F. & Huete, A. R. A review of vegetation indices. *Remote Sens. Rev.* **13,** 95–120 (1995).

Barnes, E. *et al.* Coincident detection of crop water stress, nitrogen status and canopy density using ground-based multispectral data. in *Proc. Fifth Int. Conf. Precis. Agric.* 15 (2000).

Beeri, O., Phillips, R., Hendrickson, J., Frank, A. B. & Kronberg, S. Estimating forage quantity and quality using aerial hyperspectral imagery for northern mixed-grass prairie. *Remote Sens. Environ.* **110,** 216–225 (2007).

Bombelli, A. Assessment of the status of the development of the standards for the terrestrial essential climate variables: biomass. *GTO Syst. Rome, Italy. Version* **10,** 1–18 (2009).

Brandt, M., Verger, A., Diouf, A. A., Baret, F. & Samimi, C. Local vegetation trends in the sahel of mali and senegal using long time series FAPAR satellite products and field measurement (1982-2010). *Remote Sens.* **6,** 2408–2434 (2014).

Brantley, S. T., Zinnert, J. C. & Young, D. R. Application of hyperspectral vegetation indices to detect variations in high leaf area index temperate shrub thicket canopies. *Remote Sens. Environ.* **115,** 514–523 (2011).

Breckle, S.-W. & Wucherer, W. in *L. Use Chang. Mt. Biodivers.* 9 (2006).

Brenning, A. Spatial cross-validation and bootstrap for the assessment of prediction rules in remote sensing: The R package sperrorest. *Geosci. Remote Sens. Symp. (IGARSS), 2012 IEEE Int.* 5372–5375 (2012).

Brenning, A. Package ‘ sperrorest ’. (2012).

Brenning & Alexander. Package ‘ RSAGA ’. (2013).

Breu, T., Maselli, D. & Hurni, H. Knowledge for Sustainable Development in the Tajik Pamir Mountains. *Mt. Res. Dev.* **25,** 139–146 (2005).

Cannell, M. G. R. Woody biomass of forest stands. *For. Ecol. Manage.* **8,** 299–312 (1984).

Cho, M. a. & Skidmore, a. K. Hyperspectral predictors for monitoring biomass production in Mediterranean mountain grasslands: Majella National Park, Italy. *Int. J. Remote Sens.* **30,** 499–515 (2009).

Clevers, J. G. P. W. *et al.* Derivation of the red edge index using the MERIS standard. *Int. J. Remote Sens.* **23,** 3169–3184 (2002).

Cutler, M. E. J., Boyd, D. S., Foody, G. M. & Vetrivel, A. Estimating tropical forest biomass with a combination of SAR image texture and Landsat TM data: An assessment of predictions between regions. *ISPRS J. Photogramm. Remote Sens.* **70,** 66–77 (2012).

Deutsche Gesellschaft für Technische Zusammenarbeit (GIZ). *Development of the FGIS (Forest Geographical Information System)*. (2009).

Deutsche Gesellschaft für Technische Zusammenarbeit (GIZ). *Forestry Sector Analysis of the Republic of Tajikistan*. (2010).

Diouf, A. & Lambin, E. F. Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal. *J. Arid Environ.* **48,** 129–148 (2001).

Eckert, S. Improved Forest Biomass and Carbon Estimations Using Texture Measures from WorldView-2 Satellite Data. *Remote Sens.* **4,** 810–829 (2012).

Eisfelder, C., Kuenzer, C. & Dech, S. Derivation of biomass information for semi-arid areas using remote-sensing data. *Int. J. Remote Sens.* **33,** 2937–2984 (2012).

Eitel, J. U. H. *et al.* Broadband, red-edge information from satellites improves early stress detection in a New Mexico conifer woodland. *Remote Sens. Environ.* **115,** 3640–3646 (2011).

Friedman, A. J., Hastie, T., Simon, N., Tibshirani, R. & Hastie, M. T. Package ‘ glmnet ’. (2015).

Fuchs, H., Magdon, P., Kleinn, C. & Flessa, H. Estimating aboveground carbon in a catchment of the Siberian forest tundra: Combining satellite imagery and field inventory. *Remote Sens. Environ.* **113,** 518–531 (2009).

Gilabert, M. A., Gonzales-Piqueras, F. J., Garcıa-Haro, F. & Melia, J. A generalized soil-adjusted vegetation index. *Remote Sens. Environ.* **82,** 303–310 (2002).

Gitelson, A. A. & Merzlyak, M. N. Remot estimation of chlorophyll content in higher plant leaves. *Int. J. Remote Sens.* **18,** 2691–2697 (1997).

Gitelson, A., Vina, A., Ciganda, V., Rundquist, D. C. & Arkebauer, T. J. Remote estimation of canopy chlorophyll content in crops. *Geophys. Res. Lett.* **32,** 1–4 (2005).

Gitelson, A. a, Chivkunova, O. B. & Merzlyak, M. N. Nondestructive estimation of anthocyanins and chlorophylls in anthocyanic leaves. *Am. J. Bot.* **96,** 1861–8 (2009).

Gitelson, A. & Merzlyak, M. N. Spectral Reflectance Changes Associated with Autumn Senescence of Aesculus hippocastanum L. and Acer platanoides L. Leaves. Spectral Features and Relation to Chlorophyll Estimation. *J. Plant Physiol.* **143,** 286–292 (1994).

Gray, H. R. *The form and taper of forest-tree stems*. (1956).

Haralick, R. M., Shanmugam, K. & Dinstein, I. Textural Features for Image Classification. *IEEE Trans. Syst. Man Cybern.* **3,** 610–621 (1973).

Hoeck, T., Droux, R., Breu, T., Hurni, H. & Maselli, D. Rural energy consumption and land degradation in a post-Soviet setting – an example from the west Pamir mountains in Tajikistan. *Energy Sustain. Dev.* **11,** 48–57 (2007).

Holm, A. M., Cridland, S. W. & Roderick, M. L. The use of time-integrated NOAA NDVI data and rainfall to assess landscape degradation in the arid shrubland of Western Australia. *Remote Sens. Environ.* **85,** 145–158 (2003).

Hoyer, G. E. *Tree Form Quotients as Variables in Volume Estimation*. (1985).

Huete, A. R. A Soil-Adjusted Vegetation Index (SAVI). *Remote Sens. Environ.* **25,** 295–309 (1988).

James, G., Witten, D., Hastie, T. & Tibshirani, R. *An introduction to statistical learning*. (2013). doi:10.1016/j.peva.2007.06.006

Jenkins, J. C., Chojnacky, D. C., Heath, L. S. & Birdsey, R. A. *Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species*. (2004).

Kauth, R. J. & Thomas, G. S. The tasselled cap - A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *Proc. Symp. Mach. Process. Remote. Sensed Data, West Lafayette, Indiana, U.S.A, 29 June-1 July 1976* 41–51 (1976).

Kawamura, K. *et al.* Quantifying grazing intensities using geographic information systems and satellite remote sensing in the Xilingol steppe region, Inner Mongolia, China. *Agric. Ecosyst. Environ.* **107,** 83–93 (2005).

Kelsey, K. & Neff, J. Estimates of Aboveground Biomass from Texture Analysis of Landsat Imagery. *Remote Sens.* **6,** 6407–6422 (2014).

Kraus, T. & Samimi, C. Biomass Estimation for Land Use Management and Fire Management using Landsat-TM and -ETM+. *Erdkunde* **56,** 130–143 (2002).

Kross, A., McNairn, H., Lapen, D., Sunohara, M. & Champagne, C. Assessment of RapidEye vegetation indices for estimation of leaf area index and biomass in corn and soybean crops. *Int. J. Appl. Earth Obs. Geoinf.* **34,** 235–248 (2015).

Laar, A. van & Akca, A. *Forest Mensuration*. *Science (80-.).* **24,** (2007).

Lazaridis, D. C., Verbesselt, J. & Robinson, A. P. Penalized regression techniques for prediction: a case study for predicting tree mortality using remotely sensed vegetation indices. *Can. J. For. Res.* **41,** 24–34 (2011).

Liaw, A. & Wiener, M. Package ‘ randomForest ’. *http://cran.r-project.org/web/packages/randomForest/randomForest.pdf* (2015).

Loris, V. & Damiano, G. Mapping the green herbage ratio of grasslands using both aerial and satellite-derived spectral reflectance. *Agric. Ecosyst. Environ.* **115,** 141–149 (2006).

Lu, D. Aboveground biomass estimation using Landsat TM data in the Brazilian Amazon. *Int. J. Remote Sens.* **26,** 2509–2525 (2005).

Lu, D. The potential and challenge of remote sensing-based biomass estimation. *Int. J. Remote Sens.* **27,** 1297–1328 (2006).

Luckman, A. J., Frery, A. C., Yanasse, C. C. F. & Groom, G. B. Texture in airborne SAR imagery of tropical forest and its relationship to forest regeneration stage. *Int. J. Remote Sens.* **18,** 1333–1349 (1997).

Merzlyak, M. N., Gitelson, A. A., Chivkunova, O. B., Solovchenko, A. E. & Pogosyan, S. I. Application of Reflectance Spectroscopy for Analysis of Higher Plant Pigments. **50,** 704–710 (2003).

Millennium Ecosystem Assessment. *Ecosystems and Human Well-being - Synthesis*. (2005).

Mislimshoeva, B. *et al.* Factors Influencing Households' Firewood Consumption in the Western Pamirs, Tajikistan. *Mt. Res. Dev.* **34,** 147–156 (2014).

Mueller-Dombois, D. & Ellenberg, H. *Aims and Methods of Vegetation Ecology*. (1974).

Pal, M. (2005). Random forest classifier for remote sensing classification. International Journal of Remote Sensing, 26(1), 217–222.

Powell, S. L. *et al.* Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: A comparison of empirical modeling approaches. *Remote Sens. Environ.* **114,** 1053–1068 (2010).

Qi, J., Wallace, O. & Lansing, E. Biophysical Attributes Estimation from Satellite Images in Arid Regions Jiaguo Qi and Osman Wallace. *IEEE Trans. Geosci. Remote Sens.* 2000–2003 (2002).

Safriel, U., & Adeel, Z. (2005). Dryland systems. In R. Hassan, R. Scholes, & N. Ash (Eds.), Ecosystems and human well-being: current state and trends, Vol. 1. (pp. 623–662). Washington, DC. Island Press

Sah, J. P., Ross, M. S., Koptur, S. & Snyder, J. R. Estimating aboveground biomass of broadleaved woody plants in the understory of Florida Keys pine forests. *For. Ecol. Manage.* **203,** 319–329 (2004).

Samimi, C. *Das Weidepotential im Gutu Distrikt Möglichkeiten und Grenzen der Modellierung unter Verwendung von Landsat TM-5*. (Karlsruher Schriften zur Geographie und Geoökologie, 2003).

Samimi, C. & Kraus, T. Biomass estimation using Landsat-TM and -ETM + . Towards a regional model for Southern Africa ? *GeoJournal* **59,** 177–187 (2004).

Sarker, L. R. & Nichol, J. E. Improved forest biomass estimates using ALOS AVNIR-2 texture indices. *Remote Sens. Environ.* **115,** 968–977 (2011).

Spiekermann, R., Brandt, M. & Samimi, C. Woody vegetation and land cover changes in the Sahel of Mali (1967–2011). *Int. J. Appl. Earth Obs. Geoinf.* **34,** 113–121 (2014).

Strobl, C., Boulesteix, A.-L., Zeileis, A. & Hothorn, T. Bias in random forest variable importance measures: illustrations, sources and a solution. *BMC Bioinformatics* **8,** 25 (2007).

Svoray, T. & Shoshany, M. Herbaceous biomass retrieval in habitats of complex composition: a model merging sar images with unmixed landsat tm data. *IEEE Trans. Geosci. Remote Sens.* **41,** 1592–1601 (2003).

Tucker, C. J., Vanpraet, C. L., Sharman, M. J. & Van Ittersum, G. Satellite remote sensing of total herbaceous biomass production in the senegalese sahel: 1980–1984. *Remote Sens. Environ.* **17,** 233–249 (1985).

Tucker, C. J. Red and Photographic Infrared linear Combinations for Monitoring Vegetation. *Remote Sens. Environ.* **8,** 127–150 (1979).

Vanselow, K. & Samimi, C. Predictive Mapping of Dwarf Shrub Vegetation in an Arid High Mountain Ecosystem Using Remote Sensing and Random Forests. *Remote Sens.* **6,** 6709–6726 (2014).

Verrelst, J. *et al.* Directional sensitivity analysis of vegetation indices from multi-angular CHRIS/PROBA data. (2006).

Viana, H., Cohen, W. B., Lopes, D. & Aranha, J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. *Appl. Energy* **87,** 2551–2560 (2010).

Wang, F., Huang, J., Tang, Y. & Wang, X. New Vegetation Index and Its Application in Estimating Leaf Area Index of Rice. *Rice Sci.* **14,** 195–203 (2007).

Wessels, K. J. *et al.* Relationship between herbaceous biomass and 1-km 2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa. *Int. J. Remote Sens.* **27,** 951–973 (2006).

Wiedemann, C., Salzmann, S., Mirshakarov, I. & Volkmer, H. Thermal Insulation in High Mountainous Regions. *Mt. Res. Dev.* **32,** 294–303 (2012).

Xu, B. *et al.* MODIS-based remote-sensing monitoring of the spatiotemporal patterns of China's grassland vegetation growth. *Int. J. Remote Sens.* **34,** 3867–3878 (2013).

Zandler, H., Brenning, A. & Samimi, C. (a) Quantifying dwarf shrub biomass in an arid environment: comparing empirical methods in a high dimensional setting. *Remote Sens. Environ.* **158,** 140–155 (2015).

Zandler, H., Brenning, A. & Samimi, C. (b) Potential of Space-Borne Hyperspectral Data for Biomass Quantification in an Arid Environment: Advantages and Limitations. *Remote Sens.* **7,** 4565–4580 (2015).

11.

Current pathways towards good forest governance for ecosystem services in the former Soviet republic Tajikistan

Bunafsha Mislimshoeva*[1], Peter Herbst[2] and Thomas Koellner[1]

Published in

Forest Policy and Economics 63, pp. 11-19

Peer-reviewed: March 2015. Accepted: December 2015

* Corresponding author: bunafsha.mislimshoeva@uni-bayreuth.de

[1] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstraße 30, 95440 Bayreuth, Germany

[2] Forest Legal Consultant, Wulfenstraße 15, 9500 Villach, Austria

Forest Policy and Economics 63 (2016) 11–19

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Current pathways towards good forest governance for ecosystem services in the former Soviet republic Tajikistan

Bunafsha Mislimshoeva [a,*], Peter Herbst [b], Thomas Koellner [a]

[a] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Universitätsstraße 30, 95440 Bayreuth, Germany
[b] Forest Legal Consultant, Wulfenstraße 15, 9500 Villach, Austria

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form 2 December 2015
Accepted 6 December 2015
Available online xxxx

Keywords:
Forest
good forest governance
Institutions network
Ecosystem services
Tajikistan

ABSTRACT

As one of the former Soviet republics, Tajikistan is facing a slow transition from a communist command-and-control system to a more market oriented, decentralized and participatory forestry. In the last 25 years, the country's forestry sector has undergone several reorganizations. In the process of a current reform, the overall aim of this study is to gain a broader understanding of the current state of forest sector in Tajikistan. Our specific objectives are a) to describe the current institutional network's complexity, (b) to analyze stakeholders' perceptions on the key challenges towards good forest governance, (c) and give recommendations to tackle the key challenges, so that important forest ecosystem services (ES) may be enhanced, thus, also contribute to the development of the sector. We elaborate a generic framework, which simplifies complex interaction of governance and forests ecosystem services. Quantitative and qualitative data were collected through questionnaire-based interviews with stakeholders of the forestry sector. The results indicate that the forestry sector is still far from representing good forest governance, however the newly established structure seems to be a first step. Yet, challenges in establishing sound legal frameworks, decision-making transparency, and implementation enforcement must still be overcome. While it is too early and challenging to assess the impacts of forest governance on ES and vice versa, the survey respondents highlight the importance of provisioning services for the development of the forest sector. Given the post-Soviet background, almost all member countries developed along similar lines. Therefore, the study results are not only of significance for Tajikistan, but also countries with similar history and socio-economic context.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

It is widely agreed that the state of forest ecosystems and their contribution to socio-economic development is largely dependent on the chosen governance. Poor forest governance causes depletion of these ecosystems and their consequent failure to provide sufficient goods and services to society (Lazdinis et al., 2009). While numerous definitions are in use, 'forest governance' essentially includes the "norms, processes, instruments, people, and organizations that control how local people interact with forests" (Kishor and Kenneth, 2012, p. 3). Higman et al. (2005, p. 6) argue that forest governance is about the quality of decision-making processes rather than the political governmental structures. The authors define forest governance as good governance when it encourages the implementation of sustainable forest management. In turn, good governance is associated with stakeholder participation, transparency of decision making, accountability of actors and decision makers, rule of law, predictability, efficient and effective management of natural, human, and financial resources, as well as fair and equitable allocation of resources and benefits (Kishor and Kenneth, 2012).

With a wide definition of forest governance, it is challenging to cover all aspects (Giessen and Buttoud, 2014), however, here is a common consensus that good forest governance would enhance ecosystem services (ES) of forests, as the services are tied to the sustainable management of forest resources (Ostrom, 1999; Spangenberg et al., 2014). Given this background, in the context of this study we define 'good forest governance' as a network of institutions, wherein the interaction of transparent legal frameworks, decentralized decision-making, and implementation is assumed to lead to the enhancement of ES of forests over time. This definition of good forest governance, however, would not have been relevant in the former Soviet Union. This is because forest policy in the Soviet Union is often acknowledged to be a centralized and top-down system, despite several positive aspects (Ziegler, 1990; Pryde, 1991; Nordberg, 2007; Lazdinis et al., 2009; Brain, 2011; Ulybina 2014a; Ulybina 2014b). Tajikistan, as one of the former Soviet republics, needs to cope with both the acting command-and-control system and the slow transition to market oriented, decentralized and participatory forestry. Here, during the Soviet times, "the socialistic state was the only owner of all forests" (Mukhin and Kryvda, 1976, p. 7). Thus, the state played the dominant role in defining the directions of forest policy

* Corresponding author.
E-mail address: bunafsha.mislimshoeva@uni-bayreuth.de (B. Mislimshoeva).

http://dx.doi.org/10.1016/j.forpol.2015.12.002
1389-9341/© 2015 Elsevier B.V. All rights reserved.

and its implementation. Private forestry at that period remained inconceivable because it was perceived as profit-oriented and thus, unsustainable (Koldanov, 1992). Tajikistan was in the "forest deficit zone," thus, conservation was the main aim of forestry. Wood harvesting was shifted to "forest surplus regions" such as Siberia (Pryde, 1991, pp. 115, 130). All workers of the forestry sector were employees of state cooperatives or state enterprises. In terms of implementation, forests were conserved and used only according to the plans and guidelines established by the state (Lazdinis et al., 2009; Nordberg, 2007). The inheritance of the Soviet environmental policy plays an important role in the country still today. Previously and newly established formal and informal institutions at multiple administrative levels create a complex institutional structure, which influences today's forest governance. At the same time, a lack of political attention and limited funds allocated to the forestry add further challenges towards good forest governance achievement. Additionally, the energy crisis, which occurred after the collapse of the Soviet Union in 1990 put high pressure on the already scarce forest resources (Mislimshoeva et al., 2014).

As a step towards good forest governance, i.e. better-organized institutions and more effective law enforcement, the Government of Tajikistan (GoT) declared a reform of the forestry sector in 2013. Fundamental institutional changes took place in two agencies, which are governing the country's forests: the Committee for Environment Protection (CEP) and the Forestry Agency (FA) under the Government of the Republic of Tajikistan. Before the end of 2013, the FA functioned under the command of the CEP; today the two operate independently. However, the ongoing reform process is particularly complex, due to the following challenges (Solberg and Rykowski, 2000; Kadka and Jalilova, 2013; Kohler and Kirchhoff, 2013; SPCT, 2013):

a) Weak tenure laws of forest management and lack of awareness of ownership rights; insufficient public participation in forest management;
b) A significant gap between legal frameworks, especially those on property rights and practice;
c) Lack of trained personnel;
d) Lack of reliable data on forest cover, conditions;
e) A significant lack of research in forestry sector.

To overcome these challenges, many activities are being conducted by national and international development organizations during the ongoing forest sector reform so that a decentralized and sustainable forest management system may be achieved in Tajikistan.

Not only in Tajikistan but also in other former Soviet republics forest governance topic has received very little scientific attention, despite its importance in the transition phase. In the case of Tajikistan, identifying and understanding the potential challenges of the forestry sector is essential especially in the process of the ongoing. The overall aim of this study is to gain a broader understanding of the current state of forest sector in Tajikistan. Our specific objectives are threefold: a) to describe the current institutional network's complexity, (b) to analyze stakeholders' perceptions on the key challenges towards good forest governance, (c) and give recommendations to tackle the key challenges, so that important forest ecosystem services (ES) may be enhanced, thus, also contribute to the development of the sector. The elements of the institution network, good governance and ES are explained in detail in the research framework section.

About 9–11% (around 400,000 ha) of the total pasture[1] area of Tajikistan are managed by the FA (Robinson et al. 2012; Wilkes, 2014). Pasture governance, conflicts of pasture and forest management, and implementation disputes are, however, not in the focus of this study. In-depth comparative analyses are readily available (see for example Robinson et al., 2010; Halimova, 2011; Robinson et al. 2012; Wilkes, 2014).

2. Methodology and theoretical approach

2.1. Background, forest ecosystem services and management

The Republic of Tajikistan is a landlocked country, located in the south-eastern part of Central Asia. It shares borders with Afghanistan, Uzbekistan, Kyrgyzstan, and the People's Republic of China. About 93% of its area is covered by high mountains. Almost 50% of the area is located at an elevation of more than 3000 masl (Romer, 2005; UNDP, 2008). In 1991 Tajikistan gained independence and between 1992 and 1997 it experienced a brutal civil war causing tremendous human losses and devastating the economy (UNDP, 2008). Today, Tajikistan's economy depends on exports of cotton and aluminum, while the most important factor for socio-economic stability are the remittances from labor migrants from abroad (World Bank, 2009; ADB, 2015). Poverty headcount ratio at national poverty line ($ 1.4 per capita per day) is 47% of the population (World Bank, 2009). The independence of Tajikistan and the civil war shaped the development of agriculture and forestry (Romer, 2005). Since then, these scarce resources need to sustain the increasing demand for agricultural and forest products.

Forests[2] in Tajikistan are a crucial spot of biodiversity. There are 200 species of trees and shrubs in the forests, including rare and endangered species (Kirchhoff and Fabian, 2010). The most widespread types of forests in Tajikistan are coniferous forests (*juniperus*), broadleaved forests (*mesophilous*), small-leaved mountain forests (*microthermous*), light forests (*xerophilous*), and *Tugai* forests (Novikov and Safarov, 2003; Kirchhoff and Fabian, 2010). According to the last conducted forest inventory in 1985, there were 111,200 ha of "forest covered land" in Tajikistan, covering about 0.8% of the country's land surface (Pryde, 1991, p. 114). At present, no reliable data on forest cover are available. According to the Global Forest Resources Assessment (2010) estimates the State Forest Fund[3] in Tajikistan encompass 1.8 million ha, out of which approximately 410,000 ha are actually covered by forests. This equals 3% of Tajikistan's territory. Other sources suggest that due to the ongoing human induced degradation, less than 2% are covered by forests (Kirchhoff and Fabian, 2010).

Today's forest conservation policies can be tied to the history of environmental policy in the Soviet Union. In 1943, all forests of the Union were categorized into three groups (Ulybina, 2014b). Group I included only forests under strict conservation, Group II were those of conservation and utilization, and Group III were for industrial use. Even though use of forests (including timber harvesting) was foreseen in the Forest Code of the Tajik SSR (1980, p. 109), 95.8% of its forests were under Group I, which included forests of "urban greenbelts, resorts, erosion control, shelterbelts, road protection, and forest reserves" (Pryde, 1991, p. 115–16). Thus, forests were utilized for conservation purposes, while the countries' enormous timber demand was covered by concessions in Siberia (Pryde, 1991, pp. 115, 130). Under the current Forest Code of Tajikistan (2011), conservation of forests includes areas that are important for a set of ecosystem services:

a) "water regulation — protective forest belts along rivers, lakes, reservoirs and other water bodies;
b) erosion prevention — forest on the slopes, protective strips along railways and roads;
c) sanitation and wellness — urban forests, forests around towns and other populated areas, recreational forests, and resorts;

[1] In the Forest Code (2011) pasture is defined as "land of the State Forest Fund intended for livestock grazing purposes."

[2] Forest is defined in the Forest Code (2011) as an area which is no less than 10% covered by wood-forming plants, not less than 0.5 ha and a width not less than 10 m.

[3] "The State Forest Fund comprises of all the forests of natural origin, regardless of the land user, as well as forests of artificial origin, administered by the state agencies, and lands which are not covered with forest vegetation, provided for forestry needs" (Forest Code, 2011).

d) protected areas — forest reserves, game reserves, national and natural parks, forests which have scientific, historical cultural significance;
e) nut production and fruits."

As the total forest area is relatively small, the ecological, economic, and social importance of forests is widely unrecognized. Officially the forestry sector does not play a major role in the Tajikistan's economy. The use of forest products is rather local, and only a few non-timber forest products (such as various products from sea-buckthorn, nuts, and dry fruits) are available on the national market (Kirchhoff and Fabian, 2010). The use of forests is categorized for the following purposes (Forest Code, 2011):

a) "timber harvesting and firewood;
b) secondary use for mowing, grazing, placement of hives and apiaries, breeding of seeds and seedlings, harvesting of fruits, medical and other plants;
c) scientific research, organization of cultural, recreational, tourist and sports activities;
d) construction of tourist infrastructure, recreational areas, and hunting."

The majority of forests in Tajikistan belong to the state. An extremely small share is owned by well-established non-state forest managers, comprising of former *kolkhoses*[4] (now "*dekhan* farms") and other private legal persons. From the management point of view, two main approaches are currently in place. In most of the state forests (approximately 1,790,000 ha), management approach still follows the Soviet system. Under this management system, 3000 of the FA's permanent foresters are responsible for the protection and management of the forests, who receive an annual operational plan from the FA. The number of permanent foresters has decreased drastically since 1990, however the so-called "seasonal workers" are attracted to work during the spring and autumn seasons. Both permanent foresters and seasonal workers receive extremely low salary from the FA in cash or kind (forest products). Contrastingly, in small areas of Tajikistan's forests (such as in Gorno Badakhshan Autonomous Oblast, Baljuvan, Khovaling etc.) the Joint Forest Management (JFM) approach was implemented in 2006 and has been continued since. Under JFM, the protection and management tasks are delegated from the FA to local people on the basis of 20-year contracts, which can be prolonged if there are no violations from either side. The FA and local tenants jointly develop management plans, and within the frame of these plans annual operational plans, while implementation is monitored on an annual basis by the FA and NGO representatives. Within the JFM approach, local tenants do not receive salaries but rather utilize forest products based on the agreement with the FA. Currently, 565 JFM contracts spanning 7000 ha of forests are in place (personal communication).

2.2. Research framework

The interaction of people with forests is one of the complex social-ecological systems which unconditionally require good governance. Several generic frameworks analyze this interaction. A key multilevel framework is presented by Ostrom (1999, 2009) for analyzing complex social-ecological systems, focusing on forest ecosystems and their governance. Furthermore, the FAO (Food and Agriculture Organization) and the World Bank's Program on Forests (PROFOR) elaborated a widely accepted generic Framework for Assessing and Monitoring Forest Governance which consists of generally accepted principles of good forest governance, including a) legal frameworks, b) decision-making processes, and c) implementation and enforcement (Kishor and Kenneth, 2012). However, a key challenge of frameworks as such is to measure the impact of good governance on the enhancement of forest ES and vice versa as it requires a long temporal scale (Fig. 1). Moreover, it is unlikely that all ES are enhanced simultaneously and the impact of forest governance on all provided ES is measured. Yet, to measure the impact of governance on forest ES and vice versa is possible in certain contexts where data sources are available and where the ES are prioritized according to specific interests of the forest sector. While a lack of data is the main challenge in the case of Tajikistan in order to measure the impact of governance on forest, we focus on understanding the ranking (according to importance) of ES to the forest sector from the respondents' perspective. Out of many forest ES (MA, 2005; TEEB, 2010), the following were selected based on a) the discussion with stakeholders prior to the interviews, b) their political and/or socio-economic importance, and c) their importance for forest conservation and use in Tajikistan's context:

- Provisioning Services: food (i.e. non-timber forest products), fuelwood, wood, medical plants;
- Regulating Services: erosion prevention, pollination;
- Habitat Services: habitats for species;
- Cultural Services: esthetic values, tourism.

For analyzing the application of good forest governance concept and the ES which are tied to them, we focus only on some fundamental aspects based on their rationality (Higman et al., 2005; Ostrom, 2009; Kishor and Kenneth, 2012), our experience and available literature in the region. These key aspects included institutional network, laws' consistency and compliance, transparency of decision-making and stakeholders' participation, management plans, foresters' ability to oversee their areas, and the effectiveness of cooperation.

2.3. Questionnaire elaboration

The core parts of the questionnaire (found in the supplementary material) were based on the research framework shown in Fig. 1. Except for the ES section and the management plan availability questions, the questionnaire was comprised of very broad sections and subsections, with largely open-ended questions. This gave the respondents the freedom to express their point of view on certain aspects. The questionnaire included the following sections and sub-sections:

1. Forest governance, based on the good governance principles

a) Legal framework: in this subsection questions about laws' and regulations' consistency as well as compliance of the legal framework at all levels were asked.
b) Decision-making: here, aspects, such as transparency of decisions made, stakeholders' participation, and public access to information were addressed.
c) Implementation: in this subsection, questions on salary, information technology (computers and appropriate software, Geographic Information Systems (GIS) and GPS), foresters' ability to oversee their area, and cooperation and its effectiveness were covered. Also the availability of management plans was ranked by each respondent on the scale from one (plans either do not exist or are not implemented) to ten (all forests have up-to-date plans and they are routinely implemented).

[4] A *kolkhoz* was a collective farm. This means that the land itself, was the capital and the income belonged to the workers. The income of the workers depended on the profit they made (Herbers, 2001).

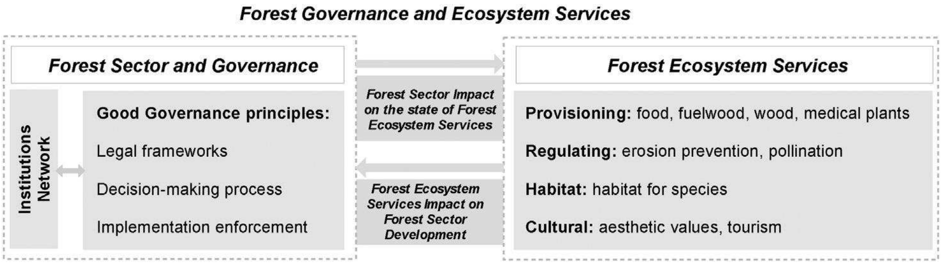


Fig. 1. Conceptual framework of this study, combining the PROFOR (Kishor and Kenneth, 2012), Ostroms' (1999, 2009) and Ecosystem Services (MA, 2005; TEEB, 2010) concepts. From this framework, we define good forest governance as a network of institutions, where the interaction of transparent legal frameworks, decentralized decision-making and implementation is assumed to lead to the enhancement of ES of forests over time. We focus on understanding the ranking (according to importance) of the ES to the forest sector from the respondents' perspective.

2. Ecosystem services (food, fuelwood, wood, medical plant, erosion prevention, pollination, habitats for species, esthetic values, tourism) importance, based on political and/or socio-economic interests

a) Importance of ES to the forestry sector: in this subsection each respondent ranked the ES according to their importance to the forestry sector (1 — least important and 8 — most important).
b) Recommended ES importance to the forestry sector: here, each respondent ranked the ES by his/her own assessment of importance for the forestry sector (1 — least important and 8 — most important).

In addition, information about forestry sector institutional setting, forest recourses and management, the successfulness of the forest policy during the Soviet era and reorganizations since the independence of Tajikistan in 1991 was included in the questionnaire.

2.4. Data collection and analysis

The data was collected in November 2014, during the process of reform in the forestry sector. In order to cover a broader range of views, we conducted 20 in-depth questionnaire-based interviews with national policy makers, international and national experts of development agencies as well as NGO representatives. The interviews were conducted with representatives from the FA (12 interviews), NGOs (3 interviews), independent consultants (1 interview), and international development agencies (4 interviews). Due to the lack of publicly-available information about potential respondents, we started the interviews within the forestry sector departments and then followed the snowball sampling method (Ulybina, 2014a). We aimed to keep the respondents diverse in terms of position, background, experience, and organization. Moreover, not all respondents answered all questions, as many did not have experience with all topics in the questionnaire. In addition to the data collected through the interviews and observations, we have used official statistics, reports, legislation, and literature (from the 1980s–90s) in order to deepen the content of the study.

The collected data on the sections and subsections of the questionnaire were categorized systematically. First, the central sections of the questionnaire (institutions network, legal framework, decision-making, implementation, importance of forest ES) were selected as overall topics. Secondly, the answers of all questionnaires within each topic were clustered and labeled accordingly as categories. This continued until all answers of each interviewee were covered by any of the categories. Thus, the categories present the viewpoint of the majority of the respondents. Several distinguished but at the same time representative statements of the respondents are cited with letter *R* (respondent) and the interviewee's identification number (e.g. *R1*). While categorizing the data, we identified the prospects and challenges for each section of the questionnaire simultaneously. As for the ES, we have visualized the rankings in a box-plot.

3. Results

3.1. Forest institutions network structure

The Forestry Agency (FA) functions under the Government of Tajikistan. It is comprised of five units on the national level, which are responsible for overall national forestry policy and management, game hunting, national parks management, and research (Fig. 2). For technical assistance and reform facilitation, FA cooperates with a number of international development agencies. On the province (*oblast*) level, the national forestry unit manages all the state forest enterprise (*leskhozes*) and cooperates with local state agencies. The *leskhozes* in turn are in charge of their subordinates (*lesnichestvo*) on the district (*rayon*) level. At this level, in cooperation with NGOs and other local state agencies, the FA implements management approaches. On the community level, the FA manages some of their forests with individual tenants under the Joint Forest Management (JFM) approach. However, permanent foresters manage the majority of the forests. Both cooperate intensively with village organizations, while tenants also work with the NGO representatives. While cooperation with other state agencies at all levels exists to an extent, in some cases it can lead to controversy. For example, due to the lack of up-to-date forest and land-use maps in most areas, there are prolonged disputes over land ownership between FA and Land Use Committee.

3.2. Reforms and reorganizations: yesterday and today

The Soviet Union's forest policy is viewed or discussed from different perspectives. Often it is perceived as a centralized and top-down policy (Ziegler, 1990; Pryde, 1991; Nordberg, 2007; Lazdinis et al., 2009; Brain, 2011; Ulybina 2014a; Ulybina 2014b). The Soviet environmental policy has been criticized for following the slogan “According to Stalin's Plan. We Will Transform Nature!” (Brain, 2011, p. 108). Yet, the transformation took place “without regard for environmental consequences” (Ziegler, 1990, p. 8). However, in Tajikistan's context, most of the experts in the field of forestry perceive the Soviet policy as a *well-structured*, *with established legal frameworks and economic strength* (*well-paid salary*, *strong capacity building*, *protection*, *implementation etc.*) (*R2–12*; *R15–17*), despite the top-down policy. This is also despite the fact that most of Tajikistan's forests were cut down for cotton production in the earlier times of the Soviet Union (Kirchhoff and Fabian, 2010). However, such agricultural land use is not appropriate for mountainous areas, where cotton never has been grown. Especially in these places (for example in the Pamir mountains), vast reforestation and afforestation (forest Group I) campaigns including the establishment of irrigation infrastructure took place in the 1960s. There was no special economic interest in forests Group I, but rather ecological and conservation (Pryde, 1991, p. 116). Also, it should be noted that at that time, there was no demand for forest products, because imported coal and gas met the energy needs of the people; *thus forest degradation from fuelwood collection was not an issue* (*R1*; *R6*; *R8*; *R17*).

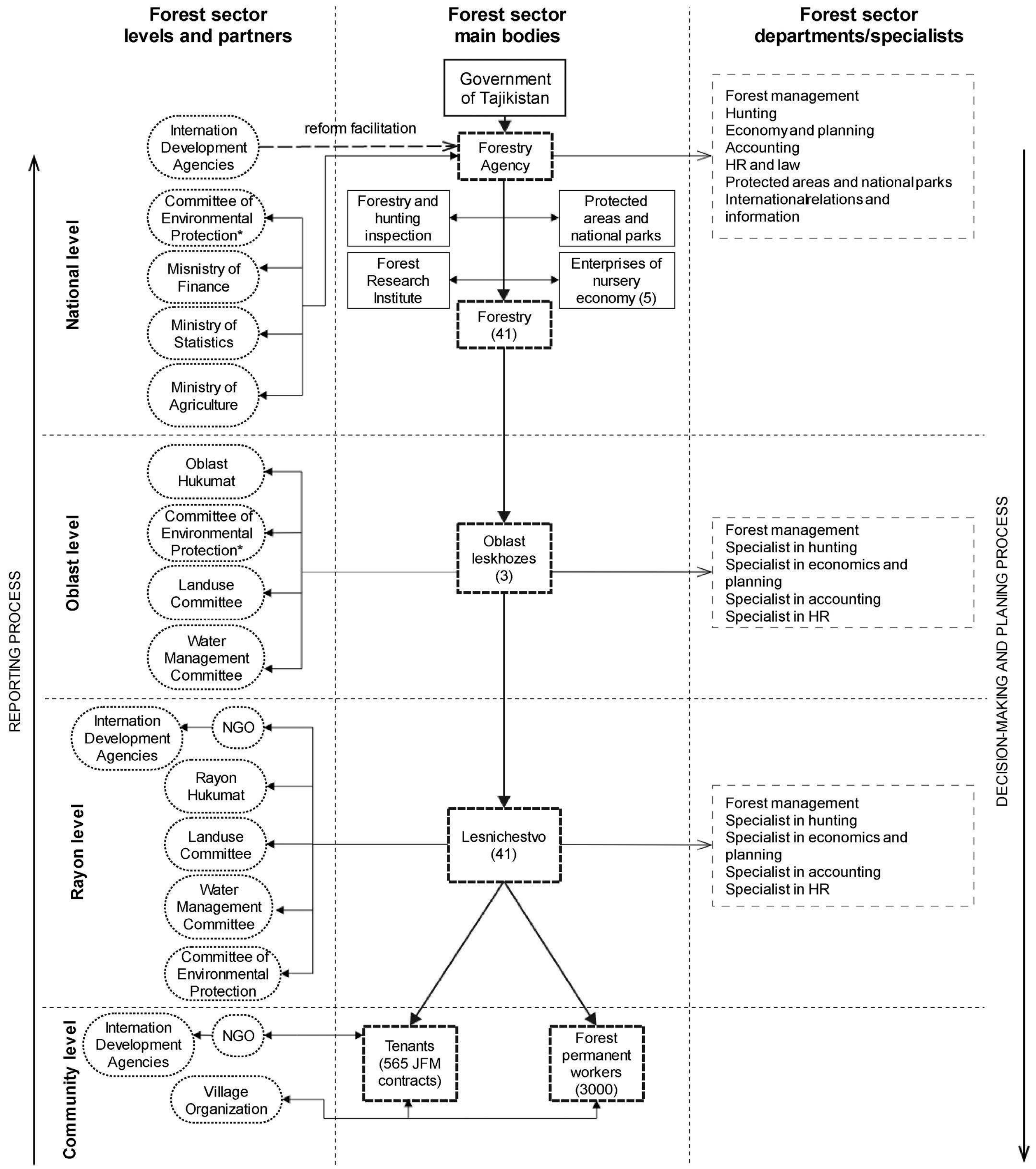


Fig. 2. The network of institutions and their interactions within and outside the forest sector. *The Forestry Agency functioned under the Committee of Environmental Protection until then end of 2013 (Source: authors' elaboration based on literature review (e.g. Kirchhoff and Fabian, 2010; Kohler and Kirchhoff, 2013; SPCT, 2013) and interviews).

To incorporate the positive aspects of the Soviet forest policy with the current framework conditions (since the independence of Tajikistan in 1991), the forestry sector has undergone seven reorganizations. All these were attempts of the Government of Tajikistan (GoT) to establish good forest governance and to find pathways towards sustainable management of forests. Despite all ambitious aims, these reorganizations regularly turned out to create controversies, and mainly resulted in the merger and/or separation of the involved institutions only (SPCT, 2013).

The forestry sector is currently undergoing another reform and reorganization process that started in 2013. The FA, an institution that previously functioned under the CEP, became an independent agency, reporting directly to the GoT. There is a consensus among the respondents, that within the CEP, the FA "*received too little attention*" (*R12*), which resulted in inefficient work processes. The inefficiency was also driven by the fact that CEP has an environmental protection (control) function, while the FA understood its function mainly as entrepreneurial. One respondent described the dilemma as, "*this is exactly the same as to have one organization which is in charge of a taxi driver and a traffic policeman*" (*R3*). Thus, the majority of the interviewees perceive the separation from the CEP to be the main reason for the continual reform. According to the experts' interviews, the 2013 reform is distinctive, because during this reform not only restructuring, but also major changes in the legal framework are envisaged. Currently, the newly accepted Forest Code (2011) plays an important role in the reform process.

3.3. Forest governance: current prospects and challenges

The reform in Tajikistan's forestry sector is ongoing, thus assessing its impact on forests remains a challenge. However, the experts' interviews identified some of the drivers of current prospects and challenges that play a crucial role during the ongoing reform and in the future. The division of the FA from the CEP was perceived to be one of the main steps towards efficiency. The independence allows the FA to directly approach the GoT and donors. As a result of this restructuring, the FA also gained a higher status within the GoT and is able to independently make decisions. From the structure point of view, the *rayon* and *oblast leskhozes* now have only one institution to which they must report, instead of two.

While the FA's new structure appears very promising on paper, many challenges remain that slow the process of implementation, according to the experts interviewed. We will highlight some of these challenges in the good governance context below (legal framework, decision-making and implementation), but they can be categorized as follows:

1. *Staff and motivation*. Lack of specialists (especially young staff) at all levels in the forestry sector; lack of capacity building for current staff; lack of motivation and interest among employees;
2. *Legal frameworks*. Conflicting and overlapping laws, especially in the CEP and FA context; weak tenure laws; financial system not adapted to the current framework conditions;
3. *Institutional setting*. Merger of several departments with distinct aims; division of departments with similar goals;
4. *Management*. Weak management and control; numerous challenges with JFM tenant system (as to introduce decentralized forest management is challenging);
5. *Research*. Absence of science-based approaches for decision-making in the forestry sector.

3.3.1. Legal framework

The previous reorganizations' controversial results can be largely attributed to the lack of a relevant and comprehensive legal basis. Even though many laws and regulations governing forests, hunting, land use, pastures, nature protection, and tenure in Tajikistan have been revised since the 1990s, their central functionality is still tied to the Soviet era. Laws explicitly include the *names of the state institutions* (*R3*, *R7*), involved in the forestry sector. Therefore, although reorganization or reform has taken place, the laws have no juridical power, resulting in conflicts among the involved institutions.

The Forest Code, adopted in 2011, aims to improve forest preservation and to provide the legal basis for the newly integrated Joint Forest Management (JFM) approach. Namely, since the acceptance of this Forest Code, JFM has been implemented in several regions of Tajikistan. However, the Forest Code is also criticized for not being consistent with the charter of the forestry sector. Also, it does not include articles describing the process of use of forest resources, forest rehabilitation, or the protection of rare trees and shrubs (SPCT, 2013).

Legal framework of forestry in Tajikistan includes, but not restricted to Forest Code, charter of the forestry sector, Nature Protection Law, the Land Code, the Law on Local State Authorities, the Code on Administrative Violence. When asked the question, "how consistent are the laws regulating the forestry sector?" 40% of the respondents answered, *most of the laws are confusing and in conflict*, while 20% responded, *some of the laws are confusing or conflict with each other*. Out of 20 respondents, only 14 had experience with law compliance. Nine of these respondents mentioned that in general *most of the laws are not followed* and *only some laws are followed*. The gap between the legal frameworks and actual implementation in the field remains a major concern of the respondents.

3.3.2. Decision-making

Transparency in decision-making is one of the key principles in good governance. However, stakeholder engagement in the decision-making process remains weak in the forestry sector. 50% of the respondents think that the FA *lacks adequate capacity to engage stakeholders on forest-related decision-making processes*. Most of the important decisions, regarding the harvest of non-timber forest products or firewood, are made centrally. *Oblast* and *rayon leskhozes* are then informed in writing, and need to comply by reaching the target. International development agencies, as reform facilitators, has supported the integration of stakeholders in the decision-making over the last two years.

Improving the transparency of decision-making is also important in enhancing the public's access to information (such as databases, statistics, maps, management plans, laws, and budgets). Access to information promotes public debate of decisions within the forestry sector. Experts cite the absence of information management system as the main obstacle to the access of information. According to 40% of the experts interviewed, most of the information is available on personal request by the interested persons. In this case, accessibility is dependent on the type of information. The quality of the accessed information also remains a major concern of the respondents.

3.3.3. Implementation

Effective implementation is a product of well-established laws and transparent decisions. Because both of the latter have yet to be achieved, the implementation phase is consequently difficult. Nevertheless, implementation is a key element of good governance, and was therefore covered by several questions during the interviews. The answers can be categorized as follow:

- Information technology (IT) and skilled staff. The major challenge identified is the absence of a modern database and GIS system. "There was no forest inventory after the collapse of the Soviet Union. Realistically speaking, we don't really know how much is growing where. I.e. we protect something that we don't know and we conserve something that may not exist" (R10). Up to now, old maps from the 1980s are still in use for forest management and decision-making. Since 2014, with the technical support of the Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) GmbH, a new mapping system is currently under development. However, the lack of IT specialists (also lack of specialists in general) at the FA continues to present challenges. "If in the Soviet time a certain plan needed 200 specialists to be implemented, now the same plan is still in use, but the number of specialist decreased to 20" (R10). On the rayon level, computers are available, however due to lack of IT training and unreliable electricity, especially in winter, they are not utilized to a great extent.
- Management plans. Out of 18 respondents, 17 ranked the availability of management plans between 1 and 5 (out of 10 possible), indicating that at best half of the forests have management plans. However, it has to be noticed that very broad management plans had been elaborated for each oblast. In turn, oblast leskhoz distribute the centrally elaborated plans among the rayons. "There are management plans,

but the question is how they are implemented and how they are related to the situation on the ground" (R10). When the JFM approach is implemented, very detailed management plans are elaborated with each tenant individually. However, this covers a minor part (7000 ha) of the total area of forests (420,000 ha).
- Foresters' capacity. To implement the existing management plans, foresters' capacity to oversee their areas plays an important role, as the state of the forests mainly depends on the foresters' work. Nine of the 17 respondents mentioned, less than half of the field foresters have the necessary capacity to oversee their areas. Several respondents think that the assigned areas are too large for the foresters to oversee effectively, given the field conditions, skills, and available resources. "For example, there is a forester who needs to travel 200 km to control his forest area. He has nothing, no car, no horse… In the end he is able to control only that part which he is physically able to reach. It may be questioned if he is motivated to travel these 200 km two times a week for $ 25 salary?" (R10).
- Salary. There was a consensus among the respondents (19 out of 20) that the salary (at all levels) within the sector is not adequate. For example, net salary of a forester is TJS[5]157 ($ 30), while the cost of living in Tajikistan per person (consumer basket) is TJS 257 ($ 48) (SPCT, 2013). The extremely low salary is one of the deterrents for young people, few of whom work in the forestry sector. To attract young specialists, the respondents suggested to motivate young specialists by providing a better salary than the current one (at all levels); to invest in capacity building, throughout all the departments and offer innovations; to provide a good working atmosphere by treating all fairly; and to provide a future perspective.
- Effective cooperation to promote good governance. To the question on cooperation effectiveness between forestry sectors stakeholders (FA, NGOs, international development agencies and other sectors), 11 out of 18 respondents shared the view that only some cooperation is effective. Following this, the respondents were asked about how to improve cooperation between NGOs, international development agencies, other sectors and FA. The answers are clustered in two groups:

Group related to the international development agencies and NGOs: Several international development agencies are directly or indirectly contributing to the Tajik forestry sector reform. NGOs are usually working on a contract basis with international development agencies. According to experts from the state and international/local NGOs, better coordination and communication is necessary between international development agencies working on similar projects to avoid overlapping projects. Another obstacle mentioned is the relative short duration of projects in relation to the long time scale of forest development. Additionally, some international development agencies are criticized for not being present in any discussions and being *far from reality* (*R3*; *R7*). "*Foreign partners are coming to Tajikistan with already a fixed plan or project which they developed somewhere else*" (*R10*). Another criticism, particularly of FA respondents, is that large shares of budgets are spent on (international) consultants, which at times would results in little but a good report.

Group related to FA (*and other sectors*): There is a lack of communication platforms not only among the international development agencies, but also between them and the FA. International development agencies demand more trust, concrete initiatives, and cooperation from the FA's side. "*The problem is that generally state institutions are not able to always express their ideas clearly*, *what concrete support they expect from partners*" (*R10*). Lack of specialists in the FA complicates cooperation as well. It should be noted that tackling many issues, particularly the implementation of forest policy, requires economic incentives. However, the expectation of economic incentives even for non-financial issues remains a challenge to the development of cooperation.

3.4. Forest ecosystem services importance within the forestry sector

The ranking or prioritization of ES according to their political and/or socio-economic importance is twofold. Firstly the importance of ES to the forestry sector is assessed by the respondents. Secondly, the respondents rank the ES by their own assessment of importance for the forestry sector (as recommendation). The ranking of the provisioning, regulating, supporting and cultural ES by the respondents shows that those ES important to the forestry sector have almost the same pattern as those recommended by the respondents (Fig. 3). The results show that overall, provisioning services seemed to be the most important services by trend, followed by regulating services. Within the provisioning services, NTFP (non-timber forest products), fuelwood, and wood are almost equally important, while medical plants seem to be more important to forestry sector. Of the regulating services, erosion prevention turned out to be a higher valued service than pollination. In comparison, habitats for species seem to be less important for the forestry sector, while the respondents valued it as a higher priority. The cultural services were in general the least important ES to the respondents.

4. Discussion

In the process of Tajikistan's forestry sector reform, this paper highlights the prospects and challenges towards good forest governance. One main indicator of good forest governance pathways is the establishment of a new institutional structure, which seems to be well accepted among the experts, even though it is not yet fully implemented. While the initial acceptance of the latest reorganization increases the hope for improved decentralized governance of forest resources, one could also question if it is yet another reorganization in a series of reorganizations to come. We encourage the former, optimistic attitude in further discussions.

According to the good forest governance definition, the application of a well-accepted structure requires established and transparent laws and regulations. As the data show, the legal bases of forest governance suffer from several drawbacks. The inconsistency of legal frameworks remains a particular concern of the respondents. Over the last 25 years, the success story of the revised Forest Code was an important step forward. However, to facilitate stable governance in the long run, the specific mandates in this code must be made consistent with other codes and laws, such as the Nature Protection Law, the Land Code, the Law on Local State Authorities, the Code on Administrative Violence and other relevant laws. In order to achieve consistency of laws and regulations and consequently their implementation, involvement of various stakeholders (including lawyers), is a challenging yet necessary step towards significant improvements. In line with that, involvement of different stakeholders needs to be more actively promoted by the FA. To establish transparency and goodwill among society, partners, donors and researchers, the FA should seriously consider the establishment of appropriate information systems, e.g., an Internet page.

Involvement of different stakeholders at different administrative levels is an essential principal of good forest governance. It is widely agreed among the respondents that currently the FA lacks the capacity to engage stakeholders on forest-related decision-making processes. There is a risk that without stakeholder involvement, the well-accepted structure (among the experts), the laws and decisions will have to be imposed on the *oblast* and *rayon levels*, with communities following the well-known command-and-control system. In this context, involvement of different stakeholders should be initiated and promoted by the FA, not the partners. Also, the closed nature of the decision-making processes leaves civil society to mistrust the representatives of the forestry sector. Furthermore, to strengthen foresters' capacity in the field, FA needs to start actively to involve local communities in forest

[5] $ 1 = TJS 5.30. National Bank of Tajikistan, January, 2015.

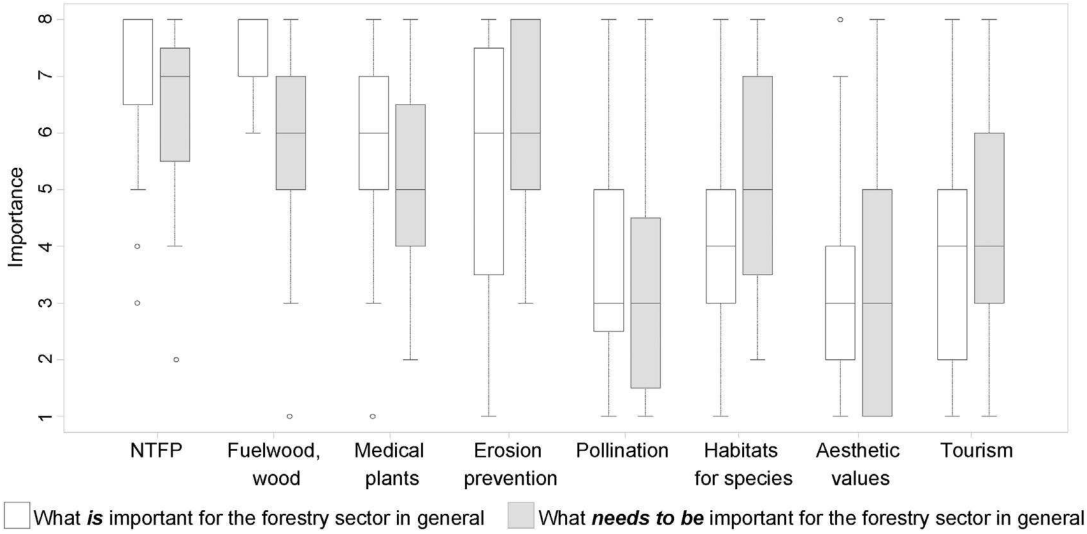


Fig. 3. Ranking (1 = unimportant and 8 = important) of ES according to their political and/or socio-economic importance. NTFP: non-timber forest products.

management, which are directly dependent on forest use. While Joint Forest Management tends to show positive results in some communities, its spatial scale remains invisible at the national level. To overcome most of these challenges, the forestry sector needs to achieve a certain financial stability, which could be reached by developing new concepts for marketing of forest provisioning services (non-timber forest products, fuelwood, wood, medical plants), which promise to be of economic importance for the sector.

As for implementation of the principle of good forest governance, the absence of basic up-to-date maps and a lack of management plans are the challenges listed by the respondents. While these are currently being dealt with, weak foresters' capacity and extremely low salaries seem to remain unchanged in the near future. With the current extremely low salaries at all levels the personnel have a little chance to fulfill their tasks.

Cooperation among institutions within the forestry sector is yet to achieve efficiency. Many challenges of the forestry sector are mutual, and will not be resolved by this sector alone. While much remains to be improved, another paradoxical point arises: the experts, who underline the weaknesses of the cooperation, are the essential part of this cooperation. This clearly shows that the important players within the forestry sectors are well aware of cooperation's drawbacks, which is not unexpected. The issue is rather the gap between knowing on the one side and taking concrete actions on the other side. Taking concrete action, however, requires first of all understanding and communication of the forest governance challenges. The involved institutions still have yet to create a common communication platform. Thus, multiple projects working on similar issues run parallel to each other, and fail to reach a common goal.

An attempt to understand the importance of ES for the Tajik forestry sector reveals that provisioning services are the most important. Even though the question during the interviews was posed in a very broad way, the respondents were most likely to answer with economic rationality. This is logical however, because it is inconceivable that e.g. cultural services would be more important than provisioning services. Although this may change in the future, at present provisioning services are more likely to provide income, thus stabilizing the financial state of the forestry sector.

The Tajik forestry sector's pathways towards sustainable forestry seem long and challenging. Yet this path can start with the creation of a holistic approach to tackle the concrete challenges that were mentioned by the experts in the context of this study. Meanwhile, however, the experts themselves being a central part of the sector, would have to embrace the movement towards change, so that the new pathways of Tajikistan's forestry sector may arise from the people driving its progress from the inside.

5. Conclusions

In conclusion, it is useful to highlight two fundamental issues of this study — one relating to methods, the other concerning the relevance of the study results. In order to understand the importance of good forest governance for ecosystem services and vice versa, in this study we develop a definition, which is then integrated into a well-established and practice-oriented conceptual framework. The framework provides a structure for empirical analysis of governance and ecosystem services, taking into account a network of institutions, wherein the interaction of transparent legal frameworks, decentralized decision-making, and implementation is assumed to lead to the enhancement services over time (in this case forest ecosystem services). The fact that this framework extends existing forest governance schemes (Ostrom, 1999; 2009; Kishor and Kenneth, 2012; Arts, 2014) by introducing ecosystem services (MA, 2005; TEEB, 2010) it is thus, powerful in simplifying complex interaction between these. In the ongoing discussion under the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) this is explicitly requested (Díaz et al., 2015). The empirical results of the framework presented in this paper provide the condition to gain overview across administrative scales and to support policies promoting good forest governance, which in turn leads to sustainable management of ecosystem services.

To measure the interaction of forest governance and ecosystem services is challenging, taking into account frequent political reforms (such as in the case of Tajikistan) and the long time scale of forest development. Given the post-Soviet background, all member countries developed along similar lines as being part of a wider Union. Therefore, currently not only in Tajikistan, but also in other countries in the region the pathway towards good forest governance is challenging (World Bank, 2005; Undeland, 2012; FLEG, 2015; ENPI FLEG, 2015). Here, at present, forest provisioning services balanced with regulating and cultural services have the potential to contribute to promoting good forest governance. While the establishment of administrative structures seems to be common, these partly continue the approach of vertical hierarchy (Undeland, 2012). Additionally, several challenges remain in establishing sound legal frameworks, decision-making transparency, and most importantly implementation. This in turn may have significant social, economic and environmental consequences (FAO, 2010).

Acknowledgments

We are very grateful to all the respondents for their time and efforts. Special thanks go to the Forestry Agency of Tajikistan and the *Deutsche Gesellschaft fuer Internationale Zusammenarbeit* (GIZ) GmbH for their valuable support. We are also thankful to the University of Bayreuth, University of Central Asia and the German Academic Exchange Service for their financial support of this research. Thank you to the excellent Editor and anonymous Reviewers for improving the quality of this article.

References

Asian Development Bank (ADB), 2015. Tajikistan.
Arts, B., 2014. Assessing forest governance from a "Triple G" perspective: government, governance, governmentality. Forest Policy and Economics, 49, 6–11. http://dx.doi.org/10.1016/j.forpol.2014.05.008
Brain, S., 2011. Song of the Forest: Russian Forestry and Stalinist Environmentalism 1905–1953. University of Pittsburgh Press, Pittsburgh.
Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., … Zlatanova, D. (2015). The IPBES Conceptual Framework — connecting nature and people. Curr. Opin. Environ. Sustain., 14, 1–16. http://dx.doi.org/10.1016/j.cosust.2014.11.002
European Neighborhood and Partnership Instrument (ENPI) East Countries Forest Law Enforcement and Governance (FLEG), 2015t. About ENPI FLEG. http://www.enpi-fleg.org
Food and Agriculture Organization (FAO), 2010. Emerging Opportunities and Challenges in Forest Finance and Forest Governance Rome, Italy.
Forest Code of Tajikistan, 2.08.2011. Лесной кодекс Республики Таджикистан. Dushanbe (in Russian).
Forest Code of the Tajik SSR, 1980. Лесной кодекс таджикской ССР. Ирфон, Душанбе. Dusnabe, Irfon (in Russian).
Forest Law Enforcement and Governance in Central Asia (FLEG), 2015). About FLEG. http://www.flermoneca.org/index.php?id=8
Giessen, L., and Buttoud, G., 2014. Defining and assessing forest governance. Forest Policy and Economics, 49, 1–3. http://dx.doi.org/10.1016/j.forpol.2014.11.009
Global Forest Resources Assessment, 2010. Forest resources assessment. Country report. Dushanbe. (accessed 3/02/2015 at http://www.fao.org/docrep/013/al640E/al640e.pdf).
Halimova, N., 2011. Pastureland tenure in Tajikistan: assessment and recommendations. Report for the Sustainable Pasture, Arable and Forest Land Management, Rural Development Project in Tajikistan ADB and GEF.
Herbers, H., 2001. Transformation in the Tajik Pamirs: Gornyi-Badakhshan—an example of successful restructuring? Central Asian Survey 20 (3), 367–381.
Higman, S., Mayers, J., Bass, S., Judd, N., Nussbaum, R., 2005. The Sustainable Forestry Handbook: A Practical Guide for Tropical Forest Managers on Implementing New Standards. ProForest Limited and International Institute for Environment and Development, London, England.
Kadka, C., Jalilova, G., 2013. Анализ Политики по Правам Пользования Лесами и Системам Совместного Управления Лесами в Афганистане, Кыргызстане и Таджикистане (Policy Analysis on Rights of Forests use and Joint Forest Management Systems in Afghanistan, Kyrgyzstan and Tajikistan) Report (in Russian).
Kirchhoff, Fabian, 2010. Forestry Sector Analysis Report. Dushanbe.
Kishor, N., Kenneth, R., 2012. Assessing and monitoring forest governance. A user's guide to a diagnostic tool. ISBN: 978-0-9855195-2-0. Washington DC, USA.
Kohler, V., Kirchhoff, J., 2013. Climate adaptation through sustainable forestry in important river catchment areas in Tajikistan. Feasibility study report Dushanbe.
Koldanov, V.Y., 1992. Очерки Истории Советского Лесного Хозяйства (Essays on the History of the Soviet Forestry). *Экология* (*Ecology*), Moscow (in Russian).
Lazdinis, M., Carver, A., Lazdinis, I., Paulikas, V., 2009. From union to union: forest governance in a post-Soviet political system. *Environ. Sci. Pol.* 12 (3), 309–320. http://dx.doi.org/10.1016/j.envsci.2008.12.004.
MA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
Mislimshoeva, B., Hable, R., Fezakov, M., Samimi, C., Koellner, T., Abdulnazarov, A., 2014. Factors influencing households' firewood consumption in the Western Pamirs, Tajikistan. Mt. Res. Dev. 34 (2), 147–156.
Mukhin, I., Kryvda, A., 1976. Леса колхозов и совхозов и ведение хозяйства в них (Forests collective and state farms and farming them). *Лесная промышленность* (*Forest industry*), Moscow (in Russian).
Nordberg, M., 2007. Ukraine reforms in forestry 1990–2000. Forest Policy and Economics 9 (6), 713–729. http://dx.doi.org/10.1016/j.forpol.2006.07.002.
Novikov, V., Safarov, N., 2003. State of the Environment in Tajikistan. (accessed 23/04/2015 at http://enrin.grida.no/htmls/tadjik/soe2001/eng/htmls/forest/state.htm)
Ostrom, E., 1999. Self-Governance and Forest Resources. CIFOR occasional paper. *62*(20). ISSN 08549818
Ostrom, E., 2009. A general framework for analyzing sustainability of social–ecological systems. Science 419. http://dx.doi.org/10.1126/science.1172133.
Pryde, P.R., 1991. Environmental Management in the Soviet Union. Cambridge University Press, Cambridge, UK.
Robinson, S., Whitton, M., Biber-Klemm, S., Muzofirshoev, N., 2010. The impact of land reform legislation on pasture tenure in Gorno-Badakhshan: from common resource to private property? Mt. Res. Dev. 30 (1), 4–13.
Robinson, S., Michel, S., Wiedemann, C., Zhumabayev,Y., Singh, N.J., 2012. Pastoral tenure in central Asia: theme and variation in the five former soviet republics. In Rangeland Stewardship in Central Asia: Balancing Improved Livelihoods, Biodiversity Conservation and Land Protection, pp. 239–274. (Ed) Victor Squires. Springer.
Romer, D., 2005. Agroforestry in Tajikistan. Report, Dushanbe. (accessed 8/02/2015 at http://www.camp.tj/images/materials/2005/Report_Agroforestry.pdf).
Solberg, B., Rykowski, K., 2000. Institutional and Legal Framework for Forest Policies in ECA Region and Selected OECD Countries — A Comparative Analysis.
Spangenberg, J.H., vonHaaren, C., Settele, J., 2014. The ecosystem service cascade: further developing the metaphor. Integrating societal processes to accommodate social processes and planning, and the case of bioenergy. Ecol. Econ. 104 (2014), 22–32.
SPCT (Союз профессиональных консультантов Таджикистана) (Union of Professional Consultants Tajikistan), 2013. Комплексный Анализ Лесного Сектора Республики Таджикистан (Comprehensive Analysis of the Forestry Sector of the Republic of Tajikistan. Report. Dushanbe) (in Russian).
TEEB (The Economics of Ecology and Biodiversity), 2010. Ecological and economic foundations. Chapter 2: Biodiversity, Ecosystems and Ecosystem Services. Earthscan, London.
Ulybina, O., 2014a. Interaction, cooperation and governance in the Russian forest sector. J. Rural. Stud. 34, 246–253. http://dx.doi.org/10.1016/j.jrurstud.2014.02.005.
Ulybina, O., 2014b. Russian forests: the path of reform. Forest Policy and Economics 38, 143–150. http://dx.doi.org/10.1016/j.forpol.2013.06.019.
Undeland, A., 2012. The Development Potential of Forests in the Kyrgyz Republic. Program on Forests (PROFOR), Washington, DC. http://www.profor.info/sites/profor.info/files/docs/ProFor%20Kyrgyz%20report_web.pdf.
UNDP (United Nations Development Programme), 2008. Tajikistan. (accessed 19/02/2015 at http://www.undp.tj/index.php?option=com_content&task=view&id=112&Itemid=162).
Wilkes, A., 2014. Institutional Analysis on Pasture Management in Tajikistan Report. Freiburg.
World Bank, 2005. Project appraisal document on forest protection and reforestation project. Report No: 33029-KZ. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2005/11/04/000012009_20051104110844/Rendered/PDF/330290rev0pdf.pdf
World Bank. 2009. Republic of Tajikistan. Poverty Assessment. Report No. 51341-TJ. Dushanbe.(accessed 20/02/2015 at https://openknowledge.worldbank.org/bitstream/handle/10986/3159/513410ESW0P112101Official0Use0Only1.pdf?sequence=1).
Ziegler, C.E., 1990. Environmental Policy in the USSR. University of Massachusetts Press, Amherst, MA.

PART III

RECOMMENDATIONS AND RESEARCH OUTLOOK

12. Main conclusions and recommendations

Under the umbrella of ecosystem services governance, supply and demand, the overall aim of this thesis was to contribute to the knowledge on energy consumption patterns, forest firewood supply-demand and governance from local case studies to a national scale based on empirical research in Tajikistan.

As for the first hypothesis, the results of the first paper indicated that firewood remains a particularly important source of energy in the rural mountainous regions of Tajikistan. However, animal dung plays the most important role, which can be explained by the fact that almost all households own animals (cows, sheep and goats), while a certain share of firewood needs to be purchased. Moreover, our field observations show that in these areas there are strong tradeoffs between energy use and agricultural activities. Animal dung is widely used as an energy source but at the same time as a fertilizer. As a result, priority is given to energy use, while the productivity of soils decreases over time; and, thus, also the quality of agricultural products. Special attention needs to be paid to the development of simple and applicable techniques for using renewable energy sources (hydro, solar, wind), to thus allow animal dung to be used for agriculture. A concrete research effort on the potentials of solar energy is currently being carried out in the western Pamirs within the framework of a project on "Transformation Processes in the Eastern Pamirs of Tajikistan: The presence and future of energy resources in the framework of sustainable development."

In relation to the first research question, the first paper showed that out of the many biophysical and socio-economic factors, elevation, size of a household's private garden and total hours of heating positively influence firewood consumption, while education level and access to a reliable supply of electricity influenced it negatively. Especially at higher elevations, where villages require more energy, but at the same have less energy sources (e.g. biomass because of the harsh climatic conditions, short vegetation period), sustainable energy production efforts, such as forestry, use of alternative sources, energy-efficient technology (e.g. thermal insulation and efficient stoves), should be considered. Moreover, higher elevation areas are especially vulnerable to the rapid changing climate and the related shifting of the vegetation period, so that planting fast growing species that are adapted to the climate change is a crucial step. Biomass remains as one of the few and important ES - not only in the research area of the thesis, but in the mountainous areas of Central Asia with very similar climatic and socio-economic conditions.

Regarding the forest firewood ES supply and demand was investigated in the second and third paper. The budget between forest firewood supply and demand remained in most cases positive, which led to the conclusion that unsustainable use of forest may not be an issue in the case study areas. This conclusion should, however, be interpreted with caution due to the lack of data on illegal firewood extraction. Several uncertainties remain in this respect, which are mentioned in detail in the second paper and in chapter 13.

The second hypothesis (and in parallel the third research question) was studied in the fourth paper, where the key challenges towards good forest governance were analyzed. The results indicated that in the forest sector of Tajikistan the establishment of a good institutional network is a first step towards good forest governance. However, challenges such as those in establishing sound legal frameworks, decision-making transparency and implementation enforcement remain to be overcome. The main policy-relevant recommendations of this study are: a) involvement of different stakeholders (mostly lawyers) is a crucial part to achieve consistency in laws and regulations, b) the Forestry Agency needs to seriously consider developing a mechanism for involving stakeholders to guarantee transparent decision-making, c) active involvement of local communities in forest management in order to increase the capacity of foresters. ES could potentially contribute to financial stability of the forest sector, and thus lead to solutions for challenges that are dependent on finance. At the same time, establishing good forest governance would lead to an enhanced management of ES, thus improving forest conditions and livelihood of communities depending on these resources.

Although the knowledge gaps are large and uncertainties attached to the available data are considerable (chapter 12), this thesis nevertheless contributes significantly to filling research gaps in the context of Tajikistan and similar countries (historically, geographically). The presented thesis contributes new empirical insights to the understanding of the energy situation in the rural areas of Tajikistan (and similar areas of Central Asia), the role of ES in the energy situation, their supply-demand and governance.

13. Research outlook

Energy consumption, firewood supply-demand and the combination with governance aspects is a complex topic, given the historical context of countries such as Tajikistan. In spite of the contribution of this thesis, this topic remains far from being fully understood, as research in this direction is still lacking considerably across scales.

This study contributes to the understanding of energy consumption patterns, while the main focus is put on firewood usage and factors influencing it. Furthermore, forest firewood supply and demand in the domestic sector is studied deeper and extended to forest governance at the national level. In the context of this study, the most challenging issue was the major lack of spatial and temporal data, which meant many results were produced at local level. Specific research outlooks are listed in each manuscript individually, while in this chapter some general points are summarized, which are mostly related to data limitations in the region:

a. Most of the case studies included in this thesis remain very local, so that their representativeness for larger spatial and longer temporal scales cannot be claimed. More studies at the province scale are necessary in order to offer a deeper understanding of energy use patterns, their impact on natural resources and direct as well as indirect driving forces of energy use across larger spatial and temporal scales. Furthermore, there is an urgent need for research replication in the area in order to strengthen the knowledge about energy demand and the role of natural energy resources in the livelihood of local population - not only of Tajikistan, but also other similar mountainous regions.
b. Due to lack of data (small sample size), the application of sophisticated methodologies in the research papers of this thesis was challenging. Thus, further data collection not only at the household level, but also small to medium industrial and public buildings could further improve the methodological limitations mentioned in this thesis. As for the forest governance aspect, more data at different administrative levels are necessary in order to capture the full picture of forest management in the country.
c. In the domestic sector, the amount of available energy sources remains largely unknown. For example, firewood sources and quantities outside of forests (e.g. from private gardens) needs further research in order to explain a wider context of firewood usage and its impact on land use and land cover across spatial and temporal scales.

A profound knowledge gap in generating quantitative and spatially explicit data about multiple ecosystem services across landscapes is challenging, and yet, a necessary step. Future research priorities should be set to further empirical and ecological data collection and to fill the knowledge gaps. For example, remote sensing is a possibility to extrapolate environmental data to a larger area. In this regards, the results of the third paper will be further analyzes to estimate forest firewood supply and spatially linked demand side. The new Sentinel sensor will provide high spatial (10 m) and temporal (3 days) resolution data, which will be available free of charge. Advanced applications for modeling ES with the InVEST tool, SWAT and/or other software and open sources will help to cover a larger spatial scale. Qualitative data for assessing peoples' perception regarding changes in the availability of ES and how these changes affect their livelihood strategies would improve the overall understanding of human dimensions of ES supply and demand. Furthermore, given a broader context of climate change in vulnerable mountainous areas of Central Asia, specific research questions could focus on a) understanding the impact of climate change on land use and, thus, on the provision of multiple ES; b) adaptation strategies when a deficiency of a certain ES exists; c) spatial and temporal ES flows, synergies and trade-offs; d) development of alternatives for increasing the supply and decreasing the demand of ES, thus reducing the pressure on natural resource.

Appendix

Conference posters and oral presentations related to this thesis are listed:

World Forestry Congress, Durban, South Africa, 7-11.09.2015. Oral presentation on: “Improving forest administration in Central Asia”

International Symposium on Legal Aspects of European Forest Sustainable Development, Brasov, Romania, 20-22.05.2015. Oral presentation on: “Forest governance in the former Soviet republic Tajikistan: current prospects and challenges”

International Conference on Ecosystem-based Adaptation to Climate Change in Central Asia, Dushanbe, Tajikistan, 9-10.04.2015. Oral presentation on: “Ecosystem based adaptation in high mountainous regions of Central Asia”

International conference of The International Society for Ecological Economics: Wellbeing and Equity within Planetary Boundaries, Reykjavik, Iceland, 13-15.08.2014. Poster presentation on: “Factors influencing households’ firewood consumption in the western Pamirs, Tajikistan”

International conference on Mobilization for Change: redefining local decision-making and participation, Bonn, Germany, 25-30.05.2013. Oral presentation on: “Analysis of firewood supply-demand chain in the Western Pamirs, Tajikistan”

Publications not being a part of this thesis:

Mislimshoeva B, Samimi C, Kirchhoff JF, Koellner T, 2013. Analysis of costs and people’s willingness to enroll in forest rehabilitation in Gorno Badakhshan, Tajikistan. *Forest Policy and Economics 37*:75–83

Zandler H, Mislimshoeva B, (under review). Scenarios of solar energy utilization on the ‘Roof of the World’: potentials and environmental benefits

Bodemeyer R, Fabian A, Mislimshoeva B, Robinson S, Yakusheva N (under review). Capacity development – key success factor for sustainable natural resource management in Central Asia.

Declaration

I hereby declare, to the best of my knowledge and belief, that this thesis does not contain any material previously published or written by another person, except where due reference has been made in the text. This thesis contains no material, which has been previously accepted or definitely rejected for award of any other doctoral degree at any university or equivalent institution.

(§ 8 S. 2 Nr. 6 PromO)

Hiermit erkläre ich mich damit einverstanden, dass die elektronische Fassung meiner Dissertation unter Wahrung meiner Urheberrechte und des Datenschutzes einer gesonderten Überprüfung hinsichtlich der eigenständigen Anfertigung der Dissertation unterzogen werden kann.

(§ 8 S. 2 Nr. 8 PromO)

Hiermit erkläre ich eidesstattlich, dass ich die Dissertation selbständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe.

(§ 8 S. 2 Nr. 9 PromO)

Ich habe die Dissertation nicht bereits zur Erlangung eines akademischen Grades anderweitig eingereicht und habe auch nicht bereits diese oder eine gleichartige Doktorprüfung endgültig nicht bestanden.

(§ 8 S. 2 Nr. 10 PromO)

Hiermit erkläre ich, dass ich keine Hilfe von gewerblichen Promotionsberatern bzw. -vermittlern in Anspruch genommen habe und auch künftig nicht nehmen werde.

Bayreuth ______________________ ________________________________

Date Bunafsha Mislimshoeva