A mathematical programming approach to model the impacts of sectoral interventions on sustainable development in rural sub-Saharan Africa

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Zusammenfassung

Unterernährung, Armut und die nicht nachhaltige Ausbeutung natürlicher Ressourcen sind schwerwiegende Probleme in Subsahara-Afrika. Überfischung und Entwaldung schädigen nicht nur die Ökosysteme, sondern gefährden auch die Existenzgrundlage der ländlichen Wirtschaftsräume. Die Förderung von Naturtourismus, Aquakultur und Bioenergieproduktion aus Papyrusbriketts stellen Möglichkeiten zur Verbesserung dar. Co-Management gewinnt immer stärker an Bedeutung in Subsahara-Afrika, um Entwicklungspläne zu erstellen und umzusetzen. Es soll einen Rahmen schaffen, in dem Regierungen eng mit den wichtigsten Interessengruppen in dörflichen Gemeinden zusammenarbeiten, allerdings häufig mit begrenztem Erfolg. Namibia und Sambia werden in dieser Arbeit als Fallstudien verwendet, da trotz Co-Management Unterernährung, Armut und eine starke Ausbeutung der natürlichen Ressourcen offensichtliche Herausforderungen darstellen. Ein Modellierungsansatz kann die Auswirkungen verschiedener Politik- (oder Entwicklungs-)Programme ex-ante bewerten, um Handlungsempfehlungen abzuleiten. Quantitative Ansätze, wie die computergestützte mathematische Programmierung, bieten daher ein wichtiges Instrument zur Unterstützung der Politikplanung und Erarbeitung von Entwicklungsmöglichkeiten, da Simulationen auf die Realisierbarkeit und wahrscheinliche Akzeptanz von Politk- (oder Entwicklungs-)Programmen hinweisen können. Es besteht folglich ein hohes Interesse an computergestützten Modellen, um die Erstellung von Entwicklungs- und Managementplänen zu unterstützen. Die Literatur verweist zudem auf Forschungsbedarf für Naturtourismus, Aquakultur und Papyrusbriketts als Bioenergie in Subsahara-Afrika. Dieser Bedarf wird im Rahmen der Arbeit durch die Entwicklung computergestützter mathematischer Programmierungsmodelle adressiert.

Vor diesem Hintergrund ist das übergeordnete Ziel dieser Arbeit, computergestützte mathematische Programmierungsmodelle zu entwickeln, um die Auswirkungen verschiedener Entwicklungsmöglichkeiten auf ländliche Ökonomien und die natürlichen Ressourcen in Subsahara-Afrika zu untersuchen. Als mögliche (Management-)Option wird der Naturtourismus und die Aquakultur am Beispiel Namibias und die Papyrusbrikettierung am Beispiel Sambias hervorgehoben. Im Einzelnen werden die folgenden Forschungsfragen aufgeworfen: (1) Verbessert der Naturtourismus die lokalen Lebensgrundlagen? (2) Hat der Naturtourismus das Potenzial, die Überfischung zu reduzieren? (3) Verbessert Aquakultur die

lokalen Lebensgrundlagen? (4) Hat Aquakultur das Potenzial, die lokale Überfischung zu reduzieren? (5) Verbessert die Papyrusernte und -verarbeitung die lokalen Lebensgrundlagen? (6) Hat die Papyrusernte und -verarbeitung das Potenzial, den Druck auf die lokalen Waldressourcen zu reduzieren?

Kapitel 2 untersucht die Auswirkungen des Naturtourismus auf die ländliche Entwicklung und den Naturschutz in Namibias Sambesi Region. Co-mangement und Naturtourismus gehen oft Hand in Hand, um den Naturerhalt und die ökonomische Entwicklung in Subsahara-Afrika zu fördern. Inwiefern sich diese beiden Strategien ergänzen, wird jedoch in der Literatur kontrovers diskutiert. Es wurde ein mathematisches Optimierungsmodell entwickelt, welches die Wirtschaft einer ländlichen Fallstudienregion repräsentiert und die Zielkonflikte zwischen Naturschutz und Entwicklungszielen untersucht. Die Datenbasis des Modells stellen Umfragedaten von 200 Haushalten aus dem Jahr 2012 dar. Es wurden zwei unterschiedliche Modellierungsszenarien entworfen. Die Ergebnisse zeigen, dass in dem Szenario der uneingeschränkten Ressourcenextraktion die lokalen Gemeinden hauptsächlich von der Fischerei und der Nutzung von Waldprodukten profitieren. Das derzeitige Problem der Überfischung wird aufgezeigt und würde durch das Fehlen des Angeltourismus noch weiter verschärft werden. Zudem zeigt die Simulation das Fehlen wichtiger Makro- und Mikronährstoffe in der täglichen Ernährung. Im Vergleich zu dieser, den Status quo repräsentierenden Modellierung zeigt das Szenario des sozialen Optimums, welches nachhaltig bewirtschaftete Fischbestände und eine angemessene Ernährung der Gemeindebewohner beinhaltet, dass die Haushalte der Gemeinde ihre landwirtschaftliche Diversifizierung erhöhen und ihre Lebensgrundlagen zugunsten von Tourismusbeschäftigungen verlagern. Solange geeignete Ernährungssubstitute für Fische zur Verfügung stehen, kann die allgemeine Wohlfahrt aufrechterhalten werden. Die Modellergebnisse zeigen die hohe Zahlungsbereitschaft für Fische von Angeltouristen im Vergleich zu lokalen Konsumenten. Aufgedeckte Marginalwerte liefern Informationen für die Entwicklung nachhaltiger regionaler Managementpläne und Richtwerte für Entwicklungsmaßnahmen. Naturtourismus hat somit das Potenzial, die Lebensgrundlagen zu verbessern und die Überfischung zu stoppen.

Kapitel 3 behandelt die Auswirkungen der Entwicklung der Aquakultur auf die Fischbestände und Lebensgrundlagen im ländlichen Namibia. Aquakultur ist allgemein als eine Möglichkeit

bekannt, Unterernährung und Armut zu reduzieren. Bisher hat sich die Forschung bezüglich dieses Themas hauptsächlich auf Asien konzentriert und die wenigen verfügbaren Studien aus Subsahara-Afrika sind überwiegend Ex-post-Teilanalysen. Daher wurde ein ländliches Gleichgewichtsmodell entwickelt, welches untersucht, ob Aquakultur die lokalen Lebensgrundlagen verbessert und gleichzeitig das Potenzial hat, der lokalen Überfischung entgegenzuwirken. Das Modell wird auf eine ländliche Fallstudienregion in der Sambesi Region Namibias angewendet, die von Unterernährung, Armut und Überfischung gekennzeichnet ist. Für die Analyse wird der Datensatz einer Sozialrechnungsmatrix aus dem Jahr 2012 verwendet. Das ländliche Gleichgewichtsmodell zeigt, dass Aquakultur eine realisierbare Aktivität zur Verbesserung des Einkommens und des Nutzens der Haushalte durch Arbeitsreallokationen ist. Darüber hinaus kann die Aquakultur der Unterernährung durch erhöhten Fischkonsum entgegenwirken. Höhere Opportunitätskosten führen dazu, dass Haushalte die Fischerei verlassen und zur Aquakultur wechseln. Diese Substitutionseffekte bieten die Möglichkeit, den Druck auf die lokalen Süßwasserfischbestände zu verringern. Die Ergebnisse prognostizieren zudem, dass der Preis für Fisch aus der Aquakultur unter dem regionalen Marktpreis liegt und somit für einkommensschwache Haushalte bezahlbar ist. Der Subsistenzfischfang übersteigt jedoch noch immer die Nachhaltigkeitsgrenze und die Simulation einer strengen Fischschutzpolitik führt zu sinkenden Einkommen und zunehmender Entwaldung. Politische Entscheidungsträger können diese Resultate nutzen, um Förderprogramme für Aquakultur in ländlichen Gebieten einzuführen. Die Ergebnisse deuten darauf hin, dass bei diesen Maßnahmen insbesondere die ärmsten Haushalte, die am stärksten von der Fischerei abhängig sind, berücksichtigt werden sollten. Abgeleitete Opportunitätskosten geben Aufschluss über Zahlungen, die notwendig sind, um politische Interventionen für verschiedene Haushaltsgruppen akzeptabel zu gestalten.

Kapitel 4 analysiert die Auswirkungen der Einführung eines Papyrusbrikettbetriebes im ländlichen Sambia. Papyrus wird zunehmend als eine alternative Bioenergiequelle vorgeschlagen, um den Druck auf die Waldökosysteme zu verringern. Es gibt jedoch nur wenige Studien über die Wirtschaftlichkeit von Papyrus-Feuchtgebieten und den Nutzen für die lokale Bevölkerung. Es wurde ein ländliches Gleichgewichtsmodell entwickelt, um zu untersuchen, ob die Ernte und Verarbeitung von Papyrus das Potenzial hat, die lokalen Lebensgrundlagen zu verbessern und gleichzeitig dem Druck auf die lokalen Waldressourcen

entgegenzuwirken. Das Modell wird auf ein Dorf im Norden Sambias angewendet, wo die Ausbeutung der Wälder zur Energiegewinnung aus Feuerholz und Holzkohle ein schwerwiegendes Problem darstellt. Die Analyse verwendet eine Sozialrechnungsmatrix, die auf Erhebungsdaten von 105 Haushalten aus dem Jahr 2015 basiert. Die Modellergebnisse zeigen, dass Papyrusbriketts ein möglicher alternativer Biokraftstoff sind und dass diese Technologie der Papyrusbrikettierung das Einkommen und den Nutzen der Haushalte durch Arbeitsreallokationen verbessert. Höhere Opportunitätskosten führen dazu, dass die Haushalte von der Feuerholzgewinnung und Holzkohleproduktion auf die Papyrusernte und -verarbeitung zur Erzeugung von Bioenergie wechseln. Die aufgedeckten gruppenspezifischen Opportunitätskosten der Gleichgewichtsanalyse stellen einen Anreiz für Haushalte dar, die Entwaldung zu stoppen. Der Austausch von Energie aus Feuerholz und Holzkohle durch Papyrusbriketts führt zu Substitutionseffekten zwischen Waldfläche und Feuchtgebiet und entlastet damit die lokalen Waldressourcen. Um Papyrus als alternative Biokraftstoffquelle zu erhalten, sind jedoch nachhaltige Erntemethoden erforderlich. Der Gleichgewichtsansatz ermöglicht eine gesamtwirtschaftliche Ex-ante-Analyse auf Dorfebene und kann Managemententscheidungen unterstützen, um den Erfolg von Papyrus-Bioenergie-Interventionen sicherzustellen.

Annex A beinhaltet ein Benutzerhandbuch für den Bau einer Sozialrechnungsmatrix einer ländlichen Ökonomie. Die Anwendung dieser Methodik ist auf nationaler Ebene bereits etabliert. Die Vorgehensweise zur Erstellung nationaler Sozialrechnungsmatrizen ist in der Literatur ausführlich dokumentiert. Sie kann aber auch für kleinere Ökonomien, wie ein Dorf, entwickelt werden. Studien, die sich mit dörflichen Sozialrechnungsmatrizen beschäftigen, sind selten. Zudem gibt es kaum Richtlinien zur Gestaltung. Um diese Lücke zu schließen, werden theoretische Grundlagen und Datenanforderungen diskutiert; eine hypothetische dörfliche Sozialrechnungsmatrix wird mit Hilfe numerischer Beispiele konstruiert. Anschließend wird eine Sozialrechnungsmatrix einer realen Dorf-Fallstudie aus Sambia analysiert. Es wird aufgezeigt, wie makroökonomische Indikatoren berechnet und mikroökonomische Informationen ermittelt werden können. Darüber hinaus wird erläutert, inwiefern eine dörfliche Sozialrechnungsmatrix die Datenbasis für wissenschaftliche Modellierungsansätze wie Optimierungs- und Gleichgewichtsmodelle bietet. Dörfliche Sozialrechnungsmatrizen sind somit ein nützliches Managementinstrument und unterstützen die Politikplanung auf lokaler und regionaler Ebene.

Stichwörter: Aquakultur; Bioenergie; Naturschutz; Entwicklungsmöglichkeiten; Fischressourcen; Waldressourcen; Managementinstrument; mathematische Programmierung; Naturtourismus; Ernährung; Papyrus; Politikplanung; ländliche Lebensgrundlagen; dörfliche Ökonomien; Subsahara-Afrika

Abstract

Malnutrition, poverty and the unsustainable exploitation of natural resources pose serious problems in sub-Saharan Africa (SSA). Overfishing and deforestation not only damage ecosystems, but also put livelihoods at risk in rural economies. The development of nature-based tourism, aquaculture and bioenergy production from papyrus briquettes provide opportunities for improvement. Co-management is becoming increasingly important in SSA to prepare and implement development plans. It aims to provide a framework in which governments work closely together with key stakeholders in village communities, but often success has been limited. Namibia and Zambia are used as case studies in this thesis because despite co-management, malnutrition, poverty and high exploitation of natural resources is evident. A modeling approach can evaluate the impact of different policy (or development) programs ex-ante in order to derive recommendations for action. Quantitative approaches such as computer-based mathematical programming therefore provide an important tool to support policy planning and explore development opportunities, as simulations can indicate the feasibility and potential acceptance of policy (or development) programs. As a result, there is great interest in computer-based models to support the design of development and management plans. The literature also points to research needs for nature-based tourism, aquaculture and papyrus briquettes as bioenergy in SSA. This need is addressed in this thesis by developing computer-based mathematical programming models.

Against this background, the overall objective of this thesis is to develop computer-based mathematical programming models to investigate the impact of different development opportunities on rural economies and natural resources in SSA. The focus of this thesis is on nature-based tourism and aquaculture applied to a region in Namibia, and papyrus briquetting applied to a rural area in Zambia as possible (management) options. In detail, the following research questions are raised: (1) Does nature-based tourism improve local livelihoods? (2) Does nature-based tourism have the potential to reduce overfishing? (3) Does aquaculture improve local livelihoods? (4) Does aquaculture have the potential to reduce local overfishing? (5) Does papyrus harvesting and processing improve local livelihoods? (6) Does papyrus harvesting and processing have the potential to reduce the pressure on local forest resources?

Chapter 2 investigates the impact of nature-based tourism on rural development and conservation in Namibia's Zambezi Region. Co-management and nature-based tourism often go hand in hand to drive conservation and economic development in SSA. However, the complementarity of the two strategies is controversially discussed in the literature. A mathematical optimization model was developed which represents the economy of a rural case study region and analyzes the trade-offs between nature conservation and development objectives. The model is based on survey data from 200 households collected in 2012. Two different modeling scenarios were developed. Results show that in the scenario describing unrestricted resource extraction, local communities mainly benefit from fishing and utilizing forest products. The current problem of overfishing is highlighted and would be further worsened by the absence of the angling tourism sector. Furthermore, important macro- and micronutrients are missing in the daily diets. In comparison, the scenario representing the social optimum, implying sustainably managed fish stocks and appropriate diets for community inhabitants, shows that community households increase agricultural diversification and shift livelihoods towards tourism employment. As long as appropriate dietary substitutes for fish are available, the overall welfare can be maintained. Model results indicate the high willingness to pay for fish of angling tourists compared to local consumers. Revealed marginal values provide information for developing sustainable regional management plans and guide values for development interventions. Nature-based tourism thus has the potential to improve livelihoods and stop overfishing.

Chapter 3 examines the impact of aquaculture development on fish stocks and livelihoods in rural Namibia. Aquaculture is widely recognized as a way to reduce malnutrition and poverty. So far, research with respect to aquaculture has mainly focused on Asia, and the few studies available from SSA are predominantly ex-post partial analyses. A village Computable General Equilibrium (CGE) model was constructed to investigate whether aquaculture improves local livelihoods and simultaneously has the potential to counteract local overfishing. The model is applied to a rural case study region in Namibia's Zambezi Region where malnutrition, poverty and fish resource overexploitation pose current problems. A Social Accounting Matrix (SAM) from 2012 is used as a database for the analysis. The village CGE model shows that aquaculture is a viable livelihood activity improving household incomes and utility through labor reallocations. Furthermore, aquaculture can counteract malnutrition through increased fish consumption. Higher opportunity costs lead

to households leaving the fisheries and switching to aquaculture. These substitution effects offer the possibility of reducing the pressure on local freshwater fish stocks. The results also predict that the price of fish from aquaculture is below the regional market price and thus more affordable for the poor. However, the subsistence fish harvest still exceeds the sustainability limit, and the simulation of a strict fish conservation policy leads to declining incomes and increasing deforestation. Policy makers can use the results to introduce aquaculture support programs in rural areas. The findings indicate that such interventions should take particular account of the poorest households, which are most dependent on fisheries. The derived opportunity costs provide information about payments that are necessary to make policy interventions acceptable for different household groups.

Chapter 4 analyzes the impacts of introducing a small-scale papyrus briquetting business in rural Zambia. Papyrus is increasingly suggested as an alternative bioenergy source to reduce the pressure on forest ecosystems. However, there are few studies on the economic viability of papyrus wetlands and the benefits for local communities. A village CGE model was developed to examine whether papyrus harvesting and processing has the potential to improve local livelihoods and simultaneously counteract the pressure on local forest resources. The model is applied to a village in northern Zambia where overexploitation of forest resources to produce energy from firewood and charcoal poses a serious problem. The analysis is based on a SAM, which was constructed from survey data of 105 households collected in 2015. The model results show that papyrus briquettes are a possible alternative biofuel and that this technology of papyrus briquetting improves household income and utility through labor reallocations. Higher opportunity costs lead to households switching from firewood extraction and charcoal production activities to papyrus harvesting and processing for bioenergy production. Revealed group-specific opportunity costs of the CGE analysis represent the incentive price for households to stop deforestation. Replacing energy supplies from firewood and charcoal with papyrus briquettes results in substitution effects between forest land and wetland and thereby reduces the pressure on local forest resources. However, sustainable harvesting regimes are required to maintain papyrus as an alternative biofuel source. The CGE approach allows for an economy-wide ex-ante analysis at village level and can support management decisions to ensure the success of papyrus bioenergy interventions.

Annex A contains a user manual for the construction of a SAM for a village economy. The methodology is well established at the national level. The procedure for developing national SAMs is extensively documented in literature. However, it can also be constructed for smaller economies, such as a village. Studies dealing with village SAMs are rare. In addition, there are hardly any guidelines for design. In order to complete this gap, theoretical principles and data requirements are discussed; a hypothetical village SAM is constructed by using numerical examples. Subsequently, the SAM of a real-world village case study from Zambia is analyzed. It is demonstrated how macroeconomic indicators can be calculated and microeconomic information obtained. Furthermore, a village SAM provides the database for scientific modeling approaches, such as optimization and CGE models, which are presented. Village SAMs are thus a useful management tool and support policy planning at local and regional level.

Keywords: Aquaculture; bioenergy; conservation; development opportunities; fish resources; forest resources; management tool; mathematical programming; nature-based tourism; nutrition; papyrus; policy planning; rural livelihoods; village economies; sub-Saharan Africa

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List of abbreviations

AfDB	African Development Bank
ATLAFCO	The Ministerial Conference on Fisheries Cooperation among African States Bordering the Atlantic Ocean
CBNRM	Community-Based Natural Resource Management
CGE	Computable General Equilibrium
CSO	Central Statistical Office
EcoMod	International Conference on Economic Modeling
GDP	Gross Domestic Product
GIS	Geographic Information System
GRN	Government of the Republic of Namibia
HLPE	High Level Panel of Experts
FAO	Food and Agriculture Organization
FftF	Fuel from the Field
IAPRI	Indaba Agricultural Policy Research Institute
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
HEP	Hannover Economic Papers
MIT	Massachusetts Institute of Technology
NASCO	Namibian Association of CBNRM Support Organisations
NNF	Namibia Nature Foundation
ROW	Rest of World
SAM	Social Accounting Matrix
SSA	Sub-Saharan Africa
UNDP	United Nations Development Programme
UNICEF	United Nations International Children's Emergency Fund
WFP	World Food Programme
WHO	World Health Organization
WTTC	World Travel & Tourism Council

Chapter 1: Introduction

1.1 Motivation and background

Malnutrition and poverty are serious problems in sub-Saharan Africa (SSA) (FAO et al., 2017; World Bank, 2017). Furthermore, natural resources are being unsustainably exploited. In many regions of SSA, continuous fishing has led to a drastic decline in fish stocks (Allison, 2011; Bartley et al., 2016; McClanahan et al., 2015; Welcomme et al., 2010), and the harvesting of forest resources has resulted in the degradation of forest ecosystems (Cerutti et al., 2015; HLPE, 2017; Wessels et al., 2013). However, this not only damage the ecosystems, but also put livelihoods in rural economies of SSA at risk, as fish and forests are essential for food and income generation (FAO, 2014; 2017; Kolding et al., 2015), and timber provides energy in the form of firewood and charcoal (International Energy Agency, 2010; 2014).

It is obvious that the current situation cannot continue and solutions need to be implemented. In this thesis, nature-based tourism, aquaculture and papyrus briquetting are investigated as possible development opportunities: Firstly, nature-based tourism is one way to support the development of rural communities in SSA (Adiyia et al., 2017; Boudreaux and Nelson, 2011; Van der Duim et al., 2015). Employment in the tourism sector provides opportunities to improve income and livelihoods (Ahebwa and Van der Duim, 2013; Gartner and Cukier, 2011; Naidoo et al., 2016; Snyman, 2013). Furthermore, nature-based tourism holds great potential for improving biodiversity conservation (Coria and Calfucura, 2012; Liu et al., 2012; Mbaiwa and Kolawole, 2013; Nyaupane and Poudel, 2011). Secondly, the development of aquaculture is another way of reducing malnutrition and poverty in rural areas (Belton and Thilsted, 2014; Béné et al., 2010; Nguyen et al., 2016; Toufique and Belton, 2014). Fish farming can increase fish consumption and thus contribute to a more balanced diet (Beveridge et al., 2013; Van Brakel and Ross, 2011; Villasante et al., 2015), especially through micronutrients (Kawarazuka and Béné, 2011). At the same time, it offers the possibility of reducing the pressure on natural fish stocks (Belton et al., 2014; McClanahan et al., 2015; Troell et al., 2014). Thirdly, the utilization of papyrus wetlands as an alternative source of bioenergy provides a way to reduce the degradation of forest resources (Jones et al., 2018; Morrison et al., 2014; Van Dam et al., 2014). The introduction of a new papyrus

briquetting technology offers great potential for the production of domestic fuel and provides an alternative livelihood (Banzaert, 2013; MIT's D-Lab, 2012; Morrison et al., 2013).

Co-management is becoming increasingly important in SSA's national decentralization and democratization programs to prepare and implement development plans. It aims to provide a framework in which governments at local level work closely together with key stakeholders in rural communities (Fabricius et al., 2013; Perrotton et al., 2017; Sowman and Wynberg, 2014). However, management strategies often achieve only limited success due to governments inadequate implementation capacity (Kolding and Van Zwieten, 2014; Mbaiwa and Kolawole, 2013; Mosimane and Silva, 2015; Winter et al., 2018), implying that local stakeholders have only limited opportunities to develop regional management plans (Barendse et al., 2016). Namibia and Zambia are used as case studies in this thesis. The countries are suffering from high levels of undernourishment and poverty (CSO, 2016; GRN, 2015; IAPRI, 2016; WFP, 2016), and natural resources that could be integrated into economic development plans are under increasing pressure despite co-management: In Namibia, important inland freshwaters such as the Zambezi River are identified as overfished (Cooke et al., 2016; Tweddle et al., 2015; Weyl et al., 2010). In Zambia, particularly northern regions such as the Luapula Province are marked by high deforestation (Chidumayo et al., 2016; Report of the Auditor General, 2017; Vinya et al., 2012).

Quantitative approaches, such as computer-based mathematical programming, provide an important tool to support policy planning and explore development opportunities (Hazell and Norton, 1986; Holden and Lofgren, 2005; Kaiser and Messer, 2011; Schlüter et al., 2017). Such a modeling approach can evaluate the impact of different policy (or development) programs ex-ante in order to derive recommendations for action (Ackermann and Gallagher, 2008; Robinson et al., 1999; Williams, 2013). Simulations can assess rural development opportunities as well as the resulting environmental and distributional effects and indicate the feasibility and potential acceptance of policy (or development) programs (Winter et al., 2015). A computer-based model can thus represent an interrelated management problem and be seen as a planning tool (Britz et al., 2013; Moritz et al., 2015). Mathematical programming has successfully been applied to food security, poverty and natural resource management (Arndt et al., 2012; Conrad et al., 2012; Diao et al., 2016; Gebreegziabher et al., 2016; Manning et al., 2016).

The literature, however, points to methodological gaps, especially with respect to approaches based on comprehensive data systems, economic links between sectors and actors as well as forecasting capacities (Global Panel, 2015; IFPRI, 2016). There is a great interest in computer-based models to support the design of development opportunities and management plans (Perrotton et al., 2017; Villamor et al., 2014; Winter et al., 2018; Zsuffa et al., 2014). The literature also points to research needs for nature-based tourism, aquaculture and papyrus briquettes as bioenergy in SSA, due to the high problem-solving potential of these development opportunities. Currently, regional management approaches that combine co-management with nature-based tourism are being developed (Naidoo et al., 2016; Tweddle et al., 2015; Van der Duim et al., 2015), whilst aquaculture is still at an early stage of development in SSA (Béné et al., 2016; Villasante et al., 2015; Waite et al., 2014). In addition, there is a general need for research on the utilization of papyrus wetlands and the economic evaluation of briquette production (Jones et al., 2018; Morrison et al., 2014; Van Dam et al., 2014). These gaps are addressed in this thesis by developing computer-based mathematical programming models.

1.2 Research objectives

The overall objective of this thesis is to develop computer-based mathematical programming models to investigate the impact of different development opportunities on rural economies and natural resources in SSA. Nature-based tourism and aquaculture are investigated as possible (management) options for a case study area in Namibia, and papyrus briquetting is simulated using the example of a village economy in rural Zambia. In detail, the following research questions are raised:

1. Does nature-based tourism improve local livelihoods?
2. Does nature-based tourism have the potential to reduce overfishing?
3. Does aquaculture improve local livelihoods?
4. Does aquaculture have the potential to reduce local overfishing?
5. Does papyrus harvesting and processing improve local livelihoods?
6. Does papyrus harvesting and processing have the potential to reduce the pressure on local forest resources?

1.3 Structure of the dissertation and main findings

Chapter 1 presents the motivation and background information of the topic. Furthermore, the problem statement, focused development opportunities and the mathematical programming approach are highlighted. The chapter also explains the research objectives and the structure of the thesis. Chapters 2 to 4 as well as the Annex A refer to published papers. Table 1.1 provides an overview of the articles in the dissertation.

Table 1.1: List of articles included in the dissertation. Source: Own illustration

Chapter	Title	Authors	Published in / Presented at
2	Modelling nature-based tourism impacts on rural development and conservation in Sikunga Conservancy, Namibia	Steven Gronau, Etti Winter, Ulrike Grote	Published in: Development Southern Africa (2017), 34(3), 276-294. Presented at: International Conference on Economic Modeling (EcoMod), Lisbon, Portugal, 06-08 July, 2016.
3	Aquaculture, fish resources and rural livelihoods: a village CGE analysis from Namibia's Zambezi Region	Steven Gronau, Etti Winter, Ulrike Grote	Published in: Environment, Development and Sustainability (2018). https://doi.org/10.1007/s10668-018-0212-1.
4	Papyrus, Forest Resources and Rural Livelihoods: A Village Computable General Equilibrium Analysis from Northern Zambia	Steven Gronau, Etti Winter, Ulrike Grote	Published in: Natural Resources (2018), 9, 268-296.
Annex A	Social Accounting Matrix: A user manual for village economies	Steven Gronau, Etti Winter	Published in: Hannover Economic Papers (HEP), No. 636, 2018, pp. 47.

Note: Authors' contributions to the papers are as follows: For Chapter 2-4, Steven Gronau generated the idea, collected and processed the data, developed the models, performed the analysis and wrote the papers. Etti Winter supervised the idea, methodology, data analysis and proof-reading. Ulrike Grote provided suggestions during the writing and commented the final versions of all papers. For Annex A, Steven Gronau developed and wrote the user manual. Etti Winter generated the idea and did the proof-reading.

Chapter 2 deals with the impact of nature-based tourism on rural development and conservation in Namibia's Zambezi Region. A mathematical optimization model was developed which represents the economy of a rural case study region and analyzes the trade-offs between nature conservation and development objectives. The model is based on survey data from 200 households collected in 2012. Two different scenarios were developed. In the reference scenario, which describes unrestricted resource extraction, the local community mainly benefits from fishing (in the rainy and flood season) and utilizing forest products (in the dry season). The current problem of overfishing is highlighted and would be further worsened by the absence of the angling tourism sector, as households would reallocate labor to subsistence fishing. Furthermore, important macro- and micronutrients are missing in daily diets of households. In comparison, the scenario representing the social optimum, implying sustainably managed fish stocks and appropriate diets for community inhabitants, shows that households increase agricultural diversification and shift livelihoods towards tourism development. As long as appropriate dietary substitutes for fish, especially protein, are available, the overall welfare can be maintained. The reallocation of labor towards angling tourism highlights the potential of the sector to support households to reduce their fishing activities; an expansion of the sector would increase the overall welfare. Model results indicate the high willingness to pay for fish of angling tourists compared to local consumers, as the marginal value of a fish caught by local fishers is just over 1% of the value of the fish caught by angling tourists. Revealed marginal values provide information for developing sustainable regional management plans and define values for development interventions. Nature-based tourism thus has the potential to improve livelihoods and stop overfishing if embedded in a socio-economic system in which benefits are distributed fairly.

Chapter 3 analyzes the impact of aquaculture development on fish stocks and livelihoods in rural Namibia. A village Computable General Equilibrium (CGE) model was constructed to investigate whether aquaculture improves local livelihoods and simultaneously has the potential to counteract local overfishing. The model is applied to a rural case study region in Namibia's Zambezi Region and uses the data set of a Social Accounting Matrix (SAM) based on household survey data from 2012. Village CGE simulation results indicate that household groups, classified by livelihood strategies, are below the poverty threshold, and up to 80% of individual nutrients are missing in the daily diets. Fish stocks are not managed sustainably, as the harvest level is twice as high as the sustainability rate. However, simulating the

introduction of aquaculture shows that fish farming would be a viable livelihood activity improving household incomes and utility through labor reallocations. Higher opportunity costs lead to households leaving the fisheries and switching to aquaculture. Furthermore, aquaculture can counteract malnutrition through increased fish consumption. Households improve their macro- and micronutrient intake and enjoy a more balanced diet. Substitution effects between fish from open fishery and fish from aquaculture offer the possibility of reducing the pressure on local freshwater fish stocks. Results also predict that the price of fish from aquaculture lies below the regional market price and is thus more affordable for the poor. However, the subsistence fish harvest still exceeds the sustainability limit, and the simulation of a strict fish conservation policy leads to declining incomes and increasing deforestation. Finally, the calculation of economic performance indicators shows that fish farming is a profitable management option in the region. Policy makers can use the results to introduce aquaculture support programs in rural areas. The findings indicate that such interventions should take particular account of the poorest households, which are most dependent on fisheries. The derived opportunity costs provide information about payments that are necessary to make policy interventions acceptable for different household groups.

Chapter 4 evaluates the impacts of introducing a small-scale papyrus briquetting business in a rural village in northern Zambia. A village CGE model was developed to examine whether papyrus harvesting and processing has the potential to improve local livelihoods and simultaneously counteract the pressure on local forest resources. The analysis is based on a SAM, which was constructed from survey data of 105 households collected in 2015. Baseline results show that the income of household groups, categorized by gender, is below the poverty threshold. The village economy heavily depends on forest resources, as large areas are cut down for bioenergy production, making them self-sufficient in energy supply. Papyrus plays currently no role in the energy generation of rural households. The simulation results show that papyrus briquettes would be a possible alternative biofuel and that this technology of papyrus briquetting improves household income and utility through labor reallocations. Higher opportunity costs lead to households switching from firewood extraction and charcoal production activities to papyrus harvesting and processing to produce bioenergy. Revealed group-specific opportunity costs of the CGE analysis represent the incentive price for households to stop deforestation. Energy production from papyrus requires less work (leisure increases) and thus more household labor is available for

additional production activities (consumption increases). Replacing energy supplies from firewood and charcoal with papyrus briquettes results in substitution effects between forest land and wetland and thereby reduces the pressure on local forest resources. Briquette production is increasing, while consumption of firewood and charcoal is decreasing. The model estimates that 5% more energy is produced per hectare of wetland than per hectare of forest land. However, sustainable harvesting regimes are required to maintain papyrus as an alternative biofuel source. The CGE approach allows for an economy-wide ex-ante analysis at village level and can support management decisions to ensure the success of papyrus bioenergy interventions.

Annex A describes a user manual for the construction of a SAM for a village economy. A SAM is a comprehensive data framework that typically represents the economy of a nation on a specific date. A developed matrix represents all economic transactions within an economy for a single year and displays the linkages between economic activities and the use of natural resources in one table. However, it can also be constructed for smaller economies, such as villages. Studies dealing with village SAMs are rare, and hardly any guidelines for design exist. Theoretical principles and data requirements are discussed, and a hypothetical village SAM is constructed by using numerical examples. Subsequently, a SAM of a real-world village case study from northern Zambia is analyzed. It is demonstrated how macroeconomic indicators can be calculated and microeconomic information obtained. Village SAMs are a useful management tool and support policy planning and monitoring at local and regional level. Depending on the research question, different subregions, sectors and household groups can be depicted in separate accounts to derive the impact of specific development interventions on the economy and natural resources. The SAM thus provides the basic data structure for the design of advanced computer-based mathematical programming models, such as optimization and CGE models.

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