Seeing beyond the smoke: smallholder farming in Papua New Guinea in a changing world

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This thesis is dedicated to Sawai.

Lukautim graun na bus gut!	Look after land and forests well!
Tingim laif bilong ol pikini!	Think about our children's future!

Abstract

Smallholder farming plays a crucial role in sustaining the food security and livelihoods of billions of people. Rapid social-ecological changes, including population growth, climate change and the incursion of external actors, are affecting smallholder farmers. In this thesis, I evaluate the changing social-ecological system of smallholder farming, and how interventions can support farmers to respond, using a case study in Papua New Guinea (PNG).

I focused my research on swidden cultivation (a type of smallholder farming). In PNG, the vast majority of the population depends on swidden agriculture, but current social-ecological changes are posing risks to farmers' well-being and environmental sustainability. Land tenure is relatively secure in PNG, making it worthwhile for swidden farmers to invest in solutions that allow them to respond to these changes. PNG is thus a unique and highly relevant site to study swidden agriculture in a changing world.

I used an interdisciplinary research approach to address the aims of my thesis. I started by investigating which factors may limit crops yields in swidden fields. Insect pests and seedeaters often negatively affect crops. I quantified foliar herbivory and seed disturbance (ecosystem disservices) and pest predation (an ecosystem service) in swidden fields along an elevational gradient. I found that the level of pest-related ecosystem disservices was relatively low compared to global levels, with foliar herbivory averaging 0.99%, disturbance of large seeds averaging 3.9% and disturbance of small seeds averaging 68%. The level of the ecosystem service, on the other hand, was relatively high with pest predation averaging 6.4%. Rapid and ongoing social-ecological changes, including increasing land shortages and climate change, may change these favourable patterns. Current farming practices, including establishing gardens close to forests, burning fields at the start of the cropping season and planting a variety of crops, are likely to be enhancing pest-related ecosystem services and reducing disservices. These practices may therefore form the basis for designing future interventions for optimising biotic pest control in swidden agricultural systems.

Another major limiting factor in many agricultural systems is soil quality. I investigated whether locally available fertilisers could enhance soil quality and crop yields. I established ten experimental fields on the land of swidden farmers. Three locally available fertilisers, including compost consisting of decaying banana peels, chicken manure and NPK fertiliser, were applied to different plots within each field, and soil quality and sweet potato yields were tracked over a year. In my study site, fertilisers that increased the level of available nitrogen and reduced soil moisture enhanced crop yields. For example, chicken manure increased yields by 16% and NPK fertiliser by 47%. So improving soil quality through applying fertilisers may be one way in which farmers could navigate increasing land shortages as a result of growing populations.

When identifying agricultural practices that may allow swidden farmers to respond to social-ecological changes, it is crucial to understand which interventions are welcomed by farmers. I evaluated which soil management practices farmers adopted and how information on them disseminated through the village's social network by conducting interviews at the beginning and end of the research project. I found that practices that bore resemblance to existing practices, such as applying compost, were more likely to be adopted than practices that required additional information and materials, such as applying chicken manure and NPK fertiliser. I also showed that people created meaning from the research in unexpected ways; farmers started to mulch, and to plant the specific variety of sweet potato that was used in the experimental fields, even though I did not aim to test the effect of mulching or promote any crop variety. The project also had another unintentional effect in that it changed the community's social network, with local research assistants becoming more sought-after for advice, and knowledge about the research project not flowing far from initial recipients. This shows that projects can have impacts beyond their original objectives. Enhancing our understanding of intended and unintended outcomes can improve our understanding of what interventions are useful to farmers, and how they might affect the social-ecological system of a swidden farming village.

Finally, there is a need to better understand what farmers themselves see as opportunities and challenges for their future. This is important because of the intrinsic importance of public participation, and because it can help produce more appropriate and sustainable adaptation plans. In collaboration with local farmers in PNG, I conducted a participatory photography project in which we explored local perspectives on resource management, drivers of change and adaptive strategies. Farmers highlighted that the main challenges they face included crop diseases of their cash crops, land shortages and lack of training. Farmers saw collaboration and education as key to their future as it would allow them to better manage their land and diversify their livelihoods. So there is a need to improve the wider context in which swidden farmers work, beyond increasing and intensifying yields. Research and planning processes that aim to support swidden farmers to respond to social-ecological changes should incorporate farmers' priorities.

Overall, my work shows how social-ecological changes are influencing farmers in PNG, and what interventions can help people navigate these changes. The results provide evidence for how swidden farming can continue to be a viable and sustainable way of living, now and in the future.

Tok klia

(Tok Pisin translation of the Abstract)

Pasin bilong wokim gaden long planim kaikai na kumu, em i bikpela pasin tru long sapotim laip bilong ol femili, komuniti na long kamapim gutpela sindaun. I gat ol nupela senis i wok long kamap insait long ples, bus, wara na antap long graun. Sampela ol senis olsem namba bilong manmeri i go antap, taim bilong san na ren tu i senis, na planti moa man kam insait long komuniti. Kain ol senis i wok long bagarapim ol gaden bilong ol manmeri long ples. Mi bin mekim wanpela wok painim aut long luksave na tokaut long wanem ol dispela ol senis i save kamap insait long wei bilong wokim gaden. Na tu luksave long wanem rot long halivim tru ol lain husait i save wokim gaden. Mi bin mekim wok painim aut bilong mi long wanpela liklik hap ples insait long Papua Niugini (PNG). Olgeta tingting bilong mi stap insait dispela buk.

Wok painim aut bilong mi i lukluk long pasin ol manmeri long ples i save wokim gaden, pasin bilong ol long katim bus, kukim bus, planim kaikai na bihain lusim dispela hap na go mekim wankain samting long narapela hap bus gen. Dispela kain pasin bilong wokim gaden em i bikpela tru insait long PNG. Tasol ol nupela kain senis kamapim hevi long ol lain husait i save planim kaikai na kumu. Na tu ol dispela senis i bagarapim bus, wara na graun. Insait long PNG, pasin bilong lukautim as ples graun em i bikpela tru. Long dispela as PNG em i kamap gutpela hap bilong mekim wok painim aut long lukluk long ol senis kamap long bus, wara na graun na tu ol hevi senis i bringim long pasin ol manmeri save mekim gaden. Na wankain taim painim sampla rot bai ol manmeri i save wok long planim gaden ken na lukautim bus bilong ol.

Mi bin mekim wok painim aut bilong mi long planti kain wei. Pastaim tru mi traim long painim aut wanem ol samting tru i ken bagarapim gro bilong ol kaikai na kumu long gaden. Mi painim aut olsem ol liklik binatang na ol pisin i save kaikai sid bilong ol kaikai na i save bagarapim ol kaikai long gaden. Mi bin traim long kisim tru namba bilong ol dispela binatang i save kaikai lip na sid bilong ol gaden kaikai, na namba bilong ol bikpela binatang or pisin i save kilim na kaikai

dispela ol liklik binatang bilong lip na sid bilong gaden. Sampela wok painim aut i bin soim olsem, long PNG bagarap i save kamap long binatang bilong lip na sid em i ananit long bagarap i save kamap long narapela hap graun long wol. Namba bilong ol lip binatang i save bagarapim gaden kaikai i sanap olsem 0.99 pesen, namba bilong ol binatang i save kaikai bikpela sid bilong kaikai i sanap olsem 3.9 pesen, na bagarap i save kamap long ol liklik sid i sanap olsem 68 pesen. Namba bilong ol gutpela samting bus, wara na graun i save givim i sanap osem 6.4 pesen. Tasol, dispela nupela senis i kamap hariap tru insait long ples, bus, wara na graun (kain olsem sot long graun, na senis long taim bilong sun na ren), bai i ken senisim ol gutpela pasin bilong wok gaden. Pasin bilong planim kaikai na kumu klostu long bus, katim bus na kukim ol pipia, na gras long hap bilong wok gaden bipo long yu wokim gaden, na planim kain kain ol kaikai na kumu i ken halivim long daunim ol binatang long bagarapim gaden. Dispela save i ken kamapim gutpela na strongpela pasin bilong wok gaden long bihain taim.

Narapela hevi i save daunim strong na laik bilong wok gaden em graun i no gat gris. Mi bin traim long painim aut tu wanem rot bilong halivim long givim gris long graun bai kaikai long gaden ken kamap gut. Long painim aut mi planim tenpela liklik gaden kaukau bilong skelim gris bilong graun. Mi yusim tripela fetelaisa bilong givim gris long graun. Dispela tripela fetelaisa em pipia kaikai bilong haus kuk olsem skin banana, pekpek bilong kakaruk, na marasin bilong stoa ol kolim NPK (nitrogen, phosphorus, potassium). Mi putim dispela tripela fetelaisa long olgeta liklik gaden mi wokim. Bihain mi skelim gris bilong graun na gro bilong kaukau. Dispela wok i kamap insait long wan yia. Wok painim aut i soim olsem fetelaisa we i save upim mak bilong nitrogen mineral na daunim wara long graun em i kamapim moa kaukau long graun. Tok piksa em olsem; pekpek bilong kakaruk i kamapim 16 pesen moa kaukau na NPK marasin i kamapim 47 pesen moa kaukau. Dispela i soim olsem fetelaisa i givim moa gris long graun na kamapim planti kaikai long sapotim planti manmeri na femili.

Long taim mi traim painim gutpela pasin bilong wok gaden long halivim ol manmeri long abrusim kain kain ol senis i save bagarapim gaden. Tasol em i bikpela samting tru long save wanem ol samting tru i ken halivim ol lain bilong wokim gut gaden. Mi bin traim long wok painim aut long wanem kain ol pasin ol manmeri i save wokim long lukautim graun, na wanem ol rot tru dispela kain ol save i ken i go long ol komuniti. Taim mi askim ol komuniti long wanem rot kain save i go long ol, mi painim aut olsem ol pasin bilong putim gris long graun em i stap bipo long ples na em i isi long ol manmeri i ken wokim. Tasol, narapela tupela samting, pekpek bilong kakaruk na NPK marasin em ol i no save yusim tumas bikos planti i no gat dispela tupela samting. Planti lain long ples i save yusim planti ol tingting bilong ol yet long kamapim gutpela gris bilong gaden long planim kaikai. Mi painim aut olsem planti lain i kisim ol gras na lip bilong kainkain kaikai na putim go daun long graun. Or planti manmeri i kisim sid bilong kain kaukau mi planim long blok long wok painim aut na karim i go traim planim gen long gaden bilong ol yet. Narapela samting em olsem, bihain long wok painim aut bilong mi, planti manmeri tru i kam askim ol wok man husait i halivim mi long wokim wok painim aut long ol i ken lainim ol long bihainim dispela nupela rot bilong mekim gaden. Dispela i soim tru olsem dispela wok bai gro bikpela na kamapim sampela nupela tingting gen long bihain. Em i moa gutpela long lainim moa na save gut long wanem samting kamap taim yu mekim wok painim aut bai yumi ken halivim ol manmeri long ples gut.

Long pinisim tok, ol manmeri bilong mekim gaden i mas lainim na save gut long wanem em gutpela na nogut bilong wok gaden long bihain taim. Bikpela samting em ol komuniti i mas wok bung wantaim long kamapim gutpela tingting bilong abrusim ol senis long bihain. Insait long wok painim aut bilong mi, wantaim ol manmeri bilong ples, mipela mekim wanpela photo projek. Insait long dispela projek mi askim ol manmeri i save wok strong long mekim gaden long tingting bilong bosim na lukautim ol bus, graun na wara. Mi askim ol tu long wanem ol sampela senis i kamap pinis long bus, graun na wara, na save bilong ol long abrusim ol senis i kamap pinis na kamapim gutpela sindaun. Ol i tok klia olsem bikpela hevi ol i save bungim long wok gaden em sik bilong kaikai, graun i sot long planim kaikai na i nogat gutpela lainim bilong lukautim gaden. Ol i ting olsem wok bung wantaim, wok painim aut, na skul em i bikpela samting tru. Dispela i ken halivim ol long lukautim graun bilong ol, na kamapim gutpela sindaun bihain taim. Olsem na i gat wok yet bilong skulim ol fama long tingting na pasin bilong lukautim gaden, bai ol i ken kamapim gutpela na planti kaikai long gaden bilong ol. Bihain wok painim aut i mas tingting long givim moa skul na sapot long ol fama bai ol inap long abrusim dispela ol senis i wok long kamap. Na ol lain husait i laik wokim wok painim aut mas luksave long wanem ol samting ol lain long ples i laikim tru long mekim or kamapim.

Wok painim aut bilong mi laik luksave na tok klia long ol senis i wok long kamap insait long ples, bus, wara na graun, na wanem ol rot long halivim ol manmeri long ples i ken abrusim kain ol senis i wok long kamap. Wok painim aut i soim olsem pasin bilong wok gaden em i gutpela na i ken oltaim sapotim ol manmeri long ples na ol femili bilong ol long nau na bihain taim tu.

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'You alone can do it, but you can't do it alone.'

Even though I appear to be the sole author of this thesis, this work is by far not the work of me alone. I am very grateful for the support I have received from the many people that contributed to my journey of writing this thesis.

E.J., Becky and Emilie, thank you very much for your guidance over the last four years. Your questions, comments and insights have pushed me to think clearer, organise better and aim higher. Even more importantly, you have given me the courage to develop my own vision and way of doing things. Thank you!

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Contributions

Even though I use the pronoun 'I' rather than 'we' in this thesis, all work in this thesis has benefited from the input of multiple people. The author contributions are:

Chapter 1 | Introduction

I wrote this chapter with input from Emilie Beauchamp, Rebecca J. Morris and E.J. Milner-Gulland.

Chapter 2 | Background

I wrote this chapter with input from Emilie Beauchamp, Rebecca J. Morris and E.J. Milner-Gulland.

Chapter 3 | Quantifying pest-related ecosystem services and disservices impacting smallholder agriculture along an elevational gradient in Papua New Guinea

Rebecca J. Morris, Vojtěch Novotný, Sofia Gripenberg and Owen T. Lewis conceived and designed the study. Emilie Beauchamp contributed to sampling design and field logistics. Francesca Dem and Joachim Yalang managed data collection. Joachim Yalang, Billy Bau, Sentiko Ibalim, Thomas Kuyowa, Raymond Laufa, Austin Sau, Salape Tulai and myself collected data. Phil L. Shearman contributed climate data. I performed data analyses and wrote the chapter, with input from Rebecca J. Morris, Billy Bau, Emilie Beauchamp, Sofia Gripenberg, Sentiko Ibalim, Owen T. Lewis, E.J. Milner-Gulland and Vojtěch Novotný.

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Chapter 4 | Using locally available fertilisers to enhance the yields of swidden farmers in Papua New Guinea

I conceived and designed the study with input from Rebecca J. Morris, Shen Sui, Brus Isua, Emilie Beauchamp, Jan Frouz, E.J. Milner-Gulland and Vojtěch Novotný. Shen Sui, Brus Isua, Kiole Imale, Mavis Jimbudo and myself collected data. Hana Veselá analysed the soil, leaf and tuber samples. I performed data analyses and wrote the chapter, with input from Rebecca J. Morris, Shen Sui, Brus Isua, Emilie Beauchamp, E.J. Milner-Gulland and Vojtěch Novotný.

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Chapter 5 | Quantifying unintended effects of an agroecological research project on farmers' practices and social network in Papua New Guinea

I conceived and designed the study with input from E.J. Milner-Gulland, Shen Sui, Brus Isua, Emilie Beauchamp and Rebecca J. Morris. Shen Sui, Brus Isua, Alfred Kik, Grace Luke and Jason Paliau and myself collected data. I performed data analyses with the help of Petr Matouš. I wrote the chapter, with input from E.J. Milner-Gulland, Shen Sui, Brus Isua, Emilie Beauchamp, Alfred Kik, Grace Luke, Petr Matouš, Rebecca J. Morris and Jason Paliau.

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Chapter 6 | The times are changing: understanding past, current and future resource use in rural Papua New Guinea using participatory photography

I conceived and designed the study with input from Emilie Beauchamp, Shen Sui, Brus Isua, Rebecca J. Morris and E.J. Milner-Gulland. Shen Sui, Brus Isua and myself collected data. I performed data analyses and wrote the chapter, with input from Emilie Beauchamp, Shen Sui, Brus Isua, Rebecca J. Morris and E.J. Milner-Gulland.

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Chapter 7 | Synthesis

I wrote this chapter with input from Emilie Beauchamp, Rebecca J. Morris and E.J. Milner-Gulland.

Translations for text in this thesis in Amele and Tok Pisin were done with the help of Brus Isua, Mavis Jimbudo, Grace Luke, Danny Nane, Mentap Sisol and Shen Sui.

Photographs presented in this thesis were taken by Shen Sui or myself, unless otherwise indicated.

Additional work

While studying for my DPhil I also contributed to the following research outputs:

A paper on the impacts of the 2015-16 El Niño on farmers across the tropics:

Whitfield, S., Beauchamp, E., Boyd, D. S., Burslem, D., Byg, A., Colledge, F., Cutler, M. E. J., Didena, M., Dougill, A., Foody, G., Godbold, J. A., Hazenbosch, M., Hirons, M., Speranza C. I., Jew, E., Lacambra, C., Mkwambisi, D., Moges, A., Morel, A., Morris, R. J., Novo, P., Rueda, M., Smith, H., Solan, M., Spencer, T., Thornton, A., Touza, J. and White, P. C. L. (2019) 'Exploring temporality in socio-ecological resilience through experiences of the 2015–16 El Niño across the tropics', *Global Environmental Change*, 55, pp. 1-14. doi: 10.1016/j.gloenvcha.2019.01.004.

A paper on the ethics of publishing scientific papers in the field of conservation:

Veríssimo, D., Pienkowski, T., Arias, M., Cugnière, L., Doughty, H., Hazenbosch, M., de Lange, E., Moskeland, A. and Grace, M. (2020) 'Ethical publishing in biodiversity conservation science', *Conservation and Society*, 18(3), pp. 220-225. doi: 10.4103/cs.cs_19_56.

A paper on conservationists' satisfaction with their goal progress:

Pienkowski, T., Keane, A., Castelló y Tickell, S., Hazenbosch, M., Arlidge, W. N. S., Baranyi, G., Brittain, S., de Lange, E., Khanyari, M. S., Papworth, S. and Milner-Gulland, E.J. (2021) 'Balancing making a difference with making a living in the conservation sector', *Conservation Biology*, pp. 1-13. doi: 10.1111/cobi.13846.

A paper on optimism among conservationists, which has been accepted as:

Pienkowski, T., Keane, A., de Lange, E., Khanyari, M. S., Arlidge, W. N. S., Baranyi, G., Brittain, S., Castelló y Tickell, S., Hazenbosch, M., Papworth, S. and Milner-Gulland, E.J. (2022) 'Personal traits predict conservationists' optimism about outcomes for nature', *Conservation Letters*.

A manuscript on factors influencing conservationists' mental health, which is in draft as:

Pienkowski, T., Keane, A., Castelló y Tickell, S., de Lange, E., Hazenbosch, M., Khanyari, M. S., Arlidge, W. N. S., Baranyi, G., Brittain, S., Kapoor, V., Mohan, V., Papworth, S., Ravi, R., Smit, I., Milner-Gulland, E.J. 'Protecting those who protect nature by supporting conservationists' mental well-being'.

A manuscript on the use of reflexivity within conservation, which is in draft as:

Pienkowski, T., Kiik, L., Catalano, A., Izquierdo-Tort, S., Khanyari, M. S., Kutty, R., Martins, C. S. G., Nash, F., Saif, O. Hazenbosch, M. and Sandbrook, C. 'Recognizing reflexivity in conservation practice'.

A handbook for farmers in Papua New Guinea on how to apply compost, chicken manure and NPK fertiliser, in both English and Tok Pisin:

Sui, S. and Hazenbosch, M., 'Handbook – Sweet potato project methods' *(English version)* or 'Hanbuk – Kaukau Projek ol steps' *(Tok Pisin version)*.

Awards

A story based on my fieldwork experiences in Papua New Guinea won the Speak Up for Food Security competition, which was organised by the Global Food Security programme. To hear the story, see https://www.youtube.com/watch?v=6VnHaEh020Y.

The work presented in this thesis won the 2020 Oxford Interdisciplinary Bioscience DTP Impact Award for Social Impact.

Table of contents

List of abbreviations

ASF	|	African swine flu
COVID-19	|	Coronavirus disease 2019
CRI	|	Christensen Research Institute
DAL	|	Department of Agriculture and Livestock
ENSO	|	El Niño Southern oscillation
ERGM	|	Exponential random graph model
Fig.	|	Figure
GBP	|	British pound sterling
GDP	|	Gross domestic product
GPS	|	Global positioning system
ITCZ	|	Intertropical convergence zone
Mt.	|	Mount
n	|	Sample size
NARI	|	National Agricultural Research Institute
NGBRC	|	The New Guinea Binatang Research Centre
NM	|	Not measured
No.	|	Number
ns	|	Non-significant
PGK	|	Papua New Guinean kina
PNG	|	Papua New Guinea
PNGDSP	|	Papua New Guinea Development Strategic Plan
PTC	|	Parataxonomist Training Center
SAOM	|	Stochastic actor-oriented model
s.e.	|	Standard error
SEM	|	Structural equation modelling
WEI	|	Wau Ecology Institute
WIAD	|	Watup, Inamus, Asial and Dougu
WPM	|	West Pacific monsoon
ZA	|	Zero adjusted

- Chapter 1 -

Introduction

Shen Sui looking over food gardens and forests in Ohu, Papua New Guinea.

'The only constant in life is change.'

- Heraclitus

1.1 Smallholder agriculture in a changing world

Smallholder farming plays a crucial role in providing the daily food and livelihoods of billions of people (UNCTAD, 2015). The global production of many important agricultural commodities, including fruits, pulses and roots and tubers, depends on smallholder farmers, so they play an important role in global food security (IFAD and UNEP, 2013; Ricciardi *et al.*, 2018). Smallholder farmers worldwide are currently facing rapid and interacting social-ecological changes. These include growing populations, the incursion of external actors, climate change, emerging pests and diseases, changes in regulatory frameworks and the transformation of local ecological knowledge. Farmers need to respond to these changes, and the extent to which they are able to do this has implications for both their well-being and environmental sustainability (Bennett and Dearden, 2013). The challenge is to identify solutions that can help farmers to respond that are technically appropriate yet socially welcomed and acceptable.

There is no single definition of a small farm, but the common understanding is that the unit of cultivated land is limited (usually defined as two hectares or less) and that the farm provides the principal source of food and income for the family (Cornish, 1998; Steward *et al.*, 2014). One category of smallholder agriculture that is particularly affected by social-ecological changes is swidden farming (Fan *et al.*, 2013). For an in-depth overview of swidden farming, see Chapter 2. In short, swidden is a word of Scandinavian origin and means 'land cleared by burning' (Mertz, Padoch, *et al.*, 2009). Swidden agriculture is found across large areas of the humid tropics of South America, Africa, Asia and Oceania (Heinimann *et al.*, 2017). There is a great variety in the way swidden agriculture is practised. What binds the different systems together is their use of fire, their cyclical nature and their use of long fallows (Padoch, 2018). In this type of agriculture, forest is converted to agricultural land by cutting and subsequently burning vegetation. After a short duration of cultivation, farmers move to a new area while the old area is fallowed, until the old field is ready to be cleared and cropped again (Padoch, 2018).

There is no reliable information on the number of people who rely on swidden cultivation for their livelihood, but estimates range from 40 million to one billion, with the most cited figure being 200-300 million (Mertz, Leisz, *et al.*, 2009). Although its use is declining worldwide, swidden agriculture may persist well into the second half of this century (Heinimann *et al.*, 2017), which begs the question of how swidden farmers can continue to respond to the changing environment.

1.1.1 Social-ecological changes affecting swidden farmers

Small scale swidden farmers rely on limited land for their livelihood and are thus particularly sensitive to environmental changes (Fan *et al.*, 2013). Climate change is bringing higher temperatures, changes in rainfall patterns and increased frequency and severity of extreme weather (IPCC, 2019). Changes in weather patterns have been forecast to reduce crop yields on average by 8% across Africa and South Asia by the 2050s (Knox *et al.*, 2012). Climate change may also affect the proliferation and spread of invasive crop diseases and pests, which can have additional negative impacts on yields and food security (Rosenzweig *et al.*, 2001).

Another major change affecting swidden farmers is rapid population growth in their areas (The World Bank Group, 2019b). So far, many swidden farmers have adapted to increasing populations, and therefore increasing land scarcity and demand for crops, by decreasing the length of their fallow period (Sirén, 2007; Dressler *et al.*, 2016). Reduced fallow periods have been shown to reduce soil quality and productivity in swidden fields (Bruun *et al.*, 2017; Fujinuma *et al.*, 2018), although it is unlikely that short fallow periods will eventually lead to a collapse of swidden cultivation, as is often assumed (Mertz *et al.*, 2008).

The socio-economic structures within which swidden farmers function are also changing rapidly. Swidden farmers are getting more and more integrated into the market economy and have started to grow cash crops in addition to their food crops (Mertz *et al.*, 2008). Cash crops can provide income which can be used to purchase food or services which can improve livelihoods (Cramb *et al.*, 2009; Schmidt, Mueller and Rosenbach, 2020), but specialisation may limit farmers' capacity to cope with risk and uncertainty and may ultimately increase their vulnerability to external shocks (Cramb *et al.*, 2009; van Vliet *et al.*, 2012).

There is also a rise in anti-swidden policies that aim to replace swidden agriculture with other types of land use (Pandey *et al.*, 2020), due to a push for large agricultural plantations and the rise of conservation, among other factors (Fox *et al.*, 2009). These policies can take different forms, including prohibition of swidden farming and non-recognition of customary lands (Cramb *et al.*, 2009). Insecure resource tenure is an especially pressing issue, as it may make farmers reluctant to undertake the necessary agronomic improvements to respond to social-ecological changes (Stanbury, 2020). When their land is appropriated, swidden farmers may not always have access to alternative livelihoods and may be forced into intensifying their land use or encroaching on other land, including that of protected areas (Cramb *et al.*, 2009).

Finally, as a result of ongoing social-ecological changes, local ecological knowledge of swidden farmers may be affected (Kik *et al.*, 2021). Local ecological knowledge is site-specific practices, understandings and beliefs that a group of people develop about their local ecosystems (Olsson and Folke, 2001). This knowledge is dynamic and co-evolves with social and ecological changes (Aswani, Lemahieu and Sauer, 2018). Many swidden farmers rely on local ecological knowledge in their day-to-day agricultural practices to know, for example, what crops and varieties are best adapted to local conditions (Mancini *et al.*, 2017) or how to minimise the negative impacts of insects on crops (Abate, van Huis and Ampofo, 2000). Local ecological knowledge also plays a crucial role in the sustainable management of forests (Flores and Levis, 2021). Due to cultural, economic and environmental changes, local ecological knowledge is being transformed, and in many cases eroded (Aswani, Lemahieu and Sauer, 2018). This may affect swidden farmers' adaptive resilience to social-ecological changes and also affect ecosystem health (Aswani, Lemahieu and Sauer, 2018; Flores and Levis, 2021).

1.1.2 Interventions to support swidden farmers to respond to social-ecological changes

Communities need to adapt to social-ecological changes. One way in which swidden farmers can respond to the need to feed a growing human population while protecting the natural environment and enhancing their resilience to shocks, is to increase and intensify yields on existing swidden fields (Padoch and Sunderland, 2013; Vanlauwe *et al.*, 2014). The yields of swidden farmers are often low compared to global average production levels (Bruun *et al.*, 2009), so there is scope to investigate how yields can be enhanced.

One reason that attained yields are relatively low, is that crop pests and diseases reduce the yields of swidden farmers (Gurr, Liu, *et al.*, 2016; Zou *et al.*, 2020). Their negative impacts may further exacerbate as climate change facilitates the spread of crop pests and diseases, and population growth may cause pressure on arable land to grow crops back-to-back which will favour their build-up (Johnson and Gurr, 2016). Resources often used to reduce the impact of pests and diseases, including pathogen-tested planting material, pheromone trapping and pesticides, may not be available to small farmers (Steward *et al.*, 2014; Johnson and Gurr, 2016). Thus alternative solutions need to be developed which are implementable and welcomed by swidden farmers. Optimising pest control by natural enemies to maintain and increase yields in fields and their surroundings may be a feasible strategy for swidden farmers (Bommarco, Kleijn and Potts, 2013), but there is a knowledge gap about how swidden farmers can achieve this.

Another key reason for relatively low crop yields is that the soils on which swidden farmers grow crops are relatively infertile. They lack important crop nutrients and are highly weathered, making it difficult for crops to thrive (Kukla *et al.*, 2019). Further land use intensification as a result of population growth may increase nutrient deficiencies, thus exacerbating the problem (Bourke and Harwood, 2009; Fujinuma *et al.*, 2018). Similar to pest and disease management, often-used resources to resolve the issue, such as inorganic fertilisers, may not be available to swidden farmers and thus alternative solutions need to be developed (Gay-des-Combes *et al.*, 2017; Fujinuma *et al.*, 2018). However, at the moment there is limited information on which soil fertilisation methods are most appropriate to maintain essential nutrients in swidden fields (Mukul and Herbohn, 2016).

Finally, so far most research to supporting swidden farmers to respond to social-ecological changes has focused on increasing and intensifying agricultural production. However, this may be one pathway for swidden farmers to respond to social-ecological changes, but not the panacea (Padoch and Sunderland, 2013). It may thus be useful to also think beyond increasing and intensifying yields, and investigate what other interventions swidden farmers see as helpful to how they can respond to social-ecological changes. These may include improving farmers' access to markets or information, and diversifying livelihoods.

1.1.3 Challenges to achieving changes in swidden agricultural systems

So far, much of the advice emanating from the current literature on how to respond to social-ecological changes is not implemented by small-scale farmers (Porciello *et al.*, 2020). This may be because farmers may not have access to the right information, farmers do not think proposed solutions are actually useful or they are too difficult to implement.

Many swidden farmers often do not have access to information on recommended agricultural practices to increase yields due to ineffective information dissemination systems in their areas (Takahashi, Muraoka and Otsuka, 2020). This is partly because swidden farmers are often geographically dispersed and live in regions with poor infrastructure, making agricultural extension services costly and time-consuming. Also, extension workers can sometimes feel unmotivated due to delays in funding and confusing lines of authority, causing information loss from extension agents to farmers (Bourke and Harwood, 2009; Niu and Ragasa, 2018). To complement the extension system, there has been increasing interest in researching whether and how farmers' social networks can be leveraged to promote information dissemination (Takahashi, Muraoka and Otsuka, 2020). However, whether this works, and which farmers could best be targeted, depends on the information-sharing relationships among farmers (de Lange, Milner-Gulland and Keane, 2019). Our understanding of whether making use of farmers' networks to share knowledge with each other, is limited, especially in swidden farming communities (Groce *et al.*, 2018).

The literature on small-scale farming is extensive and still growing. However, many of the studies mainly contribute to knowledge creation rather than providing practical solutions to smallholder farmers (Anonymous, 2020). So far most research has been done in labs or research stations and often involves only researchers without participation from farmers (Stathers *et al.*, 2020). This makes translating research into practice difficult. It is increasingly recognised that there is a need to engage with swidden farmers on their own terms to explore what changes they think are affecting them and what they see as their challenges and opportunities. This can help to produce interventions and plans that are actually useful to farmers (Bennett, Kadfak and Dearden, 2016). However, there are outstanding questions about how co-designing solutions would look like in practice and what methods may be of use.

Finally, farmers may also struggle to implement proposed solutions because they are not feasible to achieve. Many swidden farmers are money-poor and may not have the funds available to invest upfront in new technologies (Takahashi, Muraoka and Otsuka, 2020). Not only financial costs, but also labour costs are often important. It is sometimes assumed that swidden farmers have a lot of spare time and that it does not matter how much labour is needed to produce a certain crop. However, swidden farmers have tight schedules and tend to abandon a certain crop or practice when they believe their return to labour is inadequate (Bourke and Harwood, 2009). Moreover, best-practice recommendations are usually biased to achieving the highest possible yields (Takahashi, Muraoka and Otsuka, 2020). However, farmers may look beyond production and profitability, and perceive additional costs to a new practice related to the taste of a crop and ease of cooking (Otieno *et al.*, 2011). Better understanding the barriers that swidden farmers are facing when adopting new agricultural practices can help design solutions that are feasible for farmers to implement.

For decades, perhaps even centuries to come, swidden farming will continue to play a crucial role in the livelihoods of people and in biodiversity conservation across tropical regions (see section 2.1.3). However, there are outstanding questions about how swidden farmers can respond to rapid and ongoing social-ecological changes, and which interventions may support them (Laborde *et al.*, 2020).

1.2 The case for researching swidden farming in Papua New Guinea

Research to support swidden systems to respond to social-ecological changes is needed across the tropics (Mertz *et al.*, 2008), but especially in Papua New Guinea (PNG). More than 75% of the population in PNG depends almost entirely on swidden agriculture (Conservation and Environment Protection Authority, 2019). Typically, a family manages up to three small fields, also called ‘food gardens’, in which a combination of food and cash crops are planted. These food gardens form the basis of people’s livelihoods (Bourke and Harwood, 2009). Current social-ecological changes are posing risks to the well-being, health and food security of swidden farmers in PNG. The population is currently growing rapidly at 2% per year, and has already increased from 2.3 million people in 1960 to 8.9 million people in 2020 (The World Bank Group, 2020a). It is estimated that over 80% of food energy consumed in PNG is produced in-country, mainly by swidden farmers (Bourke and Harwood, 2009). Many people are not able to buy imported foods, either because they have limited access to goods and services or because they cannot afford it (Bourke and Harwood, 2009; Schmidt, Mueller and Rosenbach, 2020). To feed the additional mouths, increasing food production of swidden farmers in PNG is thus essential.

However, projections show that climate change will alter current weather patterns in PNG, with an expected increase in temperature of up to 1.1°C by 2030 relative to 1995 and an increase in the amount of rainfall, along with a rise in the occurrences of extremely high temperatures and rainfall (Australian Bureau of Meteorology and CSIRO, 2014). Increased temperatures and humidity can cause heat and water stress, and facilitate the spread of crop pests and diseases, while extreme temperatures or rainfall may spoil entire harvests. Increasing temperatures will also shift the elevational limits of crops. Some crops, such as banana, may grow at higher altitudes and expand their area, whereas for other crops, such as Irish potato and Arabica coffee, their lower elevational limit will increase causing their area to decrease (Bourke and Harwood, 2009). Overall, it is difficult to project how climate change is affecting and will affect food production in PNG, but it is likely to have a negative influence (The World Bank Group, 2021). Climate change and other environmental disasters are also projected to increase displacement in PNG, which would make people vulnerable to food insecurity and human ill-being (Naser, 2015).

At the same time, there is limited land available for expansion by swidden farmers in PNG. Currently, about a quarter of PNG's land is cultivated. Most of the remaining landmass is unsuitable for agricultural production because it is too steep, too cold, rainfall is too high, or the land is flooded every year (Bourke and Harwood, 2009). Furthermore, most the remaining land has a high conservation value. PNG contains the third largest area of tropical forest worldwide. The country is home to circa 7% of the world's biodiversity and at least 30% of species are thought to be endemic (Conservation and Environment Protection Authority, 2019; UNDP, 2021). In 2014, PNG's forest was already being cleared or degraded at a rate of 0.49% per year (Bryan and Shearman, 2014), mainly as a result of logging and swidden agriculture (Shearman *et al.*, 2009).

In PNG 97% of the land is under customary land tenure (Anderson, 2010), so how local communities in PNG manage their land is of fundamental importance to food security and biodiversity conservation. Because land tenure is relatively secure, there is an incentive for swidden farmers in PNG to invest in solutions that allow them to respond to ongoing changes. PNG is thus a unique and highly relevant site to study swidden agriculture in the context of social-ecological changes, which is why I focused my research on this country. For more information on PNG, see Chapter 2.

1.3 Taking an interdisciplinary research approach

The way in which swidden farming is practised is influenced by ecological factors, including the local climate, soil conditions and biota, and social factors such as access to technology, socio-political organisation of farmers and local beliefs, which change over time (Conklin, 1961). Research that aims to understand and improve swidden farming will need to address both ecological and social aspects. Any single academic discipline will not be sufficient to do so, and thus it is desirable to involve multiple disciplines in the research. In my research, I take an interdisciplinary research approach and synthesize several historically distinct disciplines, including ecology and sociology, with the goal of developing an integrated understanding of the issues affecting swidden farmers in PNG.

1.4 Aims and objectives of the thesis

The overall aim of this research is to understand the changing social-ecological system of swidden farming, through investigating which factors limit crop yields, what agricultural practices may improve yields, what factors affect interventions' feasibility and acceptability, and what are local perspectives on opportunities and challenges. The research was carried out in PNG, a country in which the farming system is still mostly based on swidden agriculture, and rapid social-ecological changes are taking place. The research aim is addressed through the following objectives:

- quantify pest-related ecosystem services and disservices in swidden agricultural systems in PNG;
- investigate which environmental factors influence pest damage and pest predation in food gardens;
- examine whether locally available fertilisers can enhance agricultural production and the length of time for which a food garden can be used by swidden farmers;

- understand whether swidden farmers are interested in adapting their soil management techniques, and barriers to adopting these practices;
- assess the role of research and social networks in the dissemination of agricultural practices through a swidden farming community;
- explore local perceptions of past, current and future resource use in rural PNG, and farmers' perspectives on their opportunities and challenges in responding to social-ecological changes.

1.5 Thesis outline

Subsequent to this introductory chapter, the thesis has the following structure (Fig. 1.1):

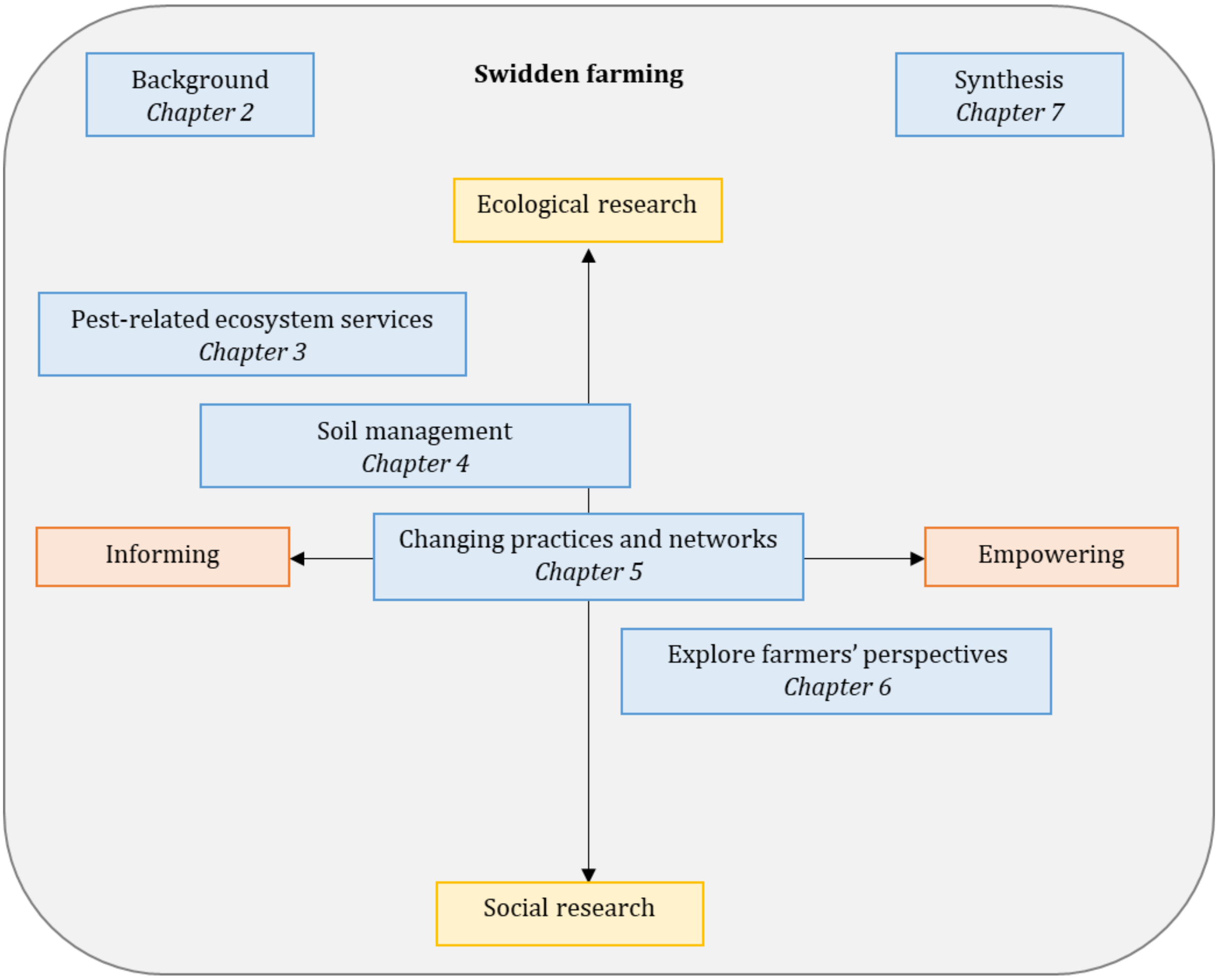

Figure 1.1 | Schematic overview of the chapters in this thesis. Work spans from research meant to generate information on swidden farming to empowering local swidden farmers to respond to social-ecological changes themselves, and combines ecological surveys with social research.

Chapter 2 provides the conceptual and contextual background in which this study has taken place. I lay out the key concepts that are relevant to this thesis, provide an introduction to PNG, give a description of the study sites, and discuss the positionality and ethics of this research.

Chapter 3 quantifies how pest-related ecosystem services and disservices impact swidden farming along an elevational gradient in PNG. Pests and pest predators provide important ecosystem disservices and services in agricultural systems, and their relative contributions affect crop yields (Oerke, 2006). Optimising ecosystem services and minimising ecosystem disservices may be a feasible strategy for small farmers to maintain and increase yields in their fields (Bommarco, Kleijn and Potts, 2013; Zou *et al.*, 2020). Research on pest-related ecosystem services and disservices has focused on large-scale farming in temperate regions, with very few studies being conducted in tropical smallholder agricultural systems (Steward *et al.*, 2014). However, this research is especially relevant now given the increasing pressures of climate change and land use intensification, which are particularly likely to change biotic pest control and impact tropical smallholder agricultural systems.

I quantified pest predation (an ecosystem service) and foliar herbivory and seed disturbance (ecosystem disservices) in food gardens of swidden farmers and their surrounding forests from which wild plants are harvested in PNG. I investigated how environmental factors including elevation, garden area, crop richness and garden age influenced pest damage and pest predation on different plant species. The results provide a reliable evidence base for how smallholder farmers in tropical countries can harness pest-related ecosystem services and reduce ecosystem disservices.

Chapter 4 describes which locally available fertilisers can enhance soil quality and increase crop yields of sweet potato (a staple in PNG), and why. Currently swidden farmers burn fields partly because it improves the physiochemical properties of the soils and thus favours crop growth (Kukla *et al.*, 2019). However, due to oxidation, volatilization, leaching and erosion, the positive effects of burning on the soil are short-lived. So there is merit in exploring additional soil fertilisation methods (Gay-des-Combes *et al.*, 2017), as it may help to increase crop yields and extend the lifetimes of agricultural fields, thereby reducing the demand to clear new land.

I worked closely with local farmers to set up experimental plots on both new and recently fallowed fields, and tested the effects of applying banana peel compost, chicken manure and NPK fertiliser on soil quality and the yields of sweet potato. Using structural equation modelling, I examined the links between soil quality and yield. I also conducted a taste test and in-depth interviews with local farmers to understand barriers to adopting soil management techniques.

Chapter 5 constitutes a rigorous evaluation of the impact of the experimental fertiliser field trial on villagers' farming practices and dissemination of information through the village's social network, using a before-after comparison. Often, researchers assume that their work may impact farmers' practices, but only at the end of a project (Bertuol-Garcia *et al.*, 2018). Some have begun to question this assumption and argue that researchers can have impact throughout their project (Toomey, Knight and Barlow, 2017). However, there are few empirical studies that pay attention to encounters that occur between researchers and non-scientists during field research (Toomey, 2016). Moreover, there is limited information on how social networks may help in disseminating information through a community in rural settings of the Global South (Groce *et al.*, 2018).

I quantified the effects of the experimental fertiliser field trial on farming practices and the social network in the village community. I conceptualised the community as a network system, and tracked the joint evolution of farming practices and the social network through simulations using stochastic actor-oriented modelling. Non-intuitive results demonstrate that the inferences that people draw from researchers' activities may be very different to those researchers are aiming to test in their research. Understanding intended and unintended effects of interventions can help identify what solutions are useful to farmers.

Chapter 6 explores what local farmers themselves see as their opportunities and challenges going forward. It is increasingly recognised that local and indigenous groups need to be engaged on their own terms and fully participate in research and planning processes aimed at supporting their communities to address social-ecological changes (Mistry and Berardi, 2016). In natural resource management and planning, participatory photography has been recognised as a useful tool to involve communities, promote dialogue and inform policy (Wang and Burris, 1997).

I applied participatory photography in a smallholder farming community in PNG to explore local perspectives on resource management, drivers of change in resource use and availability, and adaptive strategies. The participatory photography process yielded rich visual data and stories. The photographs highlighted how farmers in PNG are making complex decisions about how to manage their resources in the face of rapid social-ecological changes. These results can be used in future research and planning processes in PNG.

Chapter 7 provides a synthesis of the research findings. It summarises the key results of the research presented in this thesis, highlights the themes and concepts arising from the work and suggests directions for future research to swidden farming. I also reflect on how my thinking and research approach changed over time. I end my thesis in PNG-style by telling a story that reflects on the meaning of this thesis.

- Chapter 2 -

Background

Mama Erica planting a tree in her food garden in Ohu, Papua New Guinea.

'There is nothing as practical as a good theory.'

- Kurt Lewin

2.1 Background to swidden agriculture

2.1.1 Definition

Swidden cultivation comes in many different variations, which makes it difficult to give one encompassing definition for 'swidden agriculture' (Padoch, 2018). However, there are characteristics that these variations have in common which may constitute the elements of a definition. They include (Mertz, Padoch, *et al.*, 2009; Erni, 2015; Padoch, 2018):

- removal of natural vegetation (usually shrubs or trees), usually by cutting and subsequently burning of the land;
- an alternation between a short duration of cultivation and a comparatively long duration of fallow;
- the fallow may be natural, enhanced in which case useful tree crops either for subsistence or cash income are planted, or improved when fertilisers and herbicides are used to speed up the process of soil restoration and weed suppression;
- a regular, and often cyclical, shifting of fields.

Swidden cultivation, shifting cultivation and slash-and-burn agriculture are all systems of small-scale agriculture, and the terms are often used synonymously. However, their meanings are not identical. Fire-free, mulch-based systems are more appropriately called shifting cultivation, while slash-and-burn agriculture does not necessarily include the shifting of fields (Mertz, Padoch, *et al.*, 2009). Swidden cultivation describes well the agricultural systems of much of Papua New Guinea (PNG) and will thus be used throughout this thesis.

2.1.2 *Ecology of swidden systems*

2.1.2.1 The life cycle of a swidden field

Swidden farmers often prepare their fields before the rains are due to come (Eyzaguirre, 1986). Farmers cut down a piece of forest, frequently secondary forest, with sizes ranging from a few square meters to several hectares in the case multiple households choose to farm contiguously (Vira, Wildburger and Mansourian, 2015). However, useful tree species are usually spared and left standing as they can provide food, help suppress weeds, prevent soil erosion and speed up the ecological succession process during the fallow period (Vira, Wildburger and Mansourian, 2015). Often fire gets used to burn the cut vegetation and clear the land for cropping, but it also helps to kill pests and part of the weed seed bank, and convert the nutrients accumulated in the above-ground biomass to plant available forms (Bruun *et al.*, 2009).

After space has been created, a great variety of crops get intercropped, with the types of crops planted changing from place to place and time to time (Padoch, 2018). The biodiversity in swidden farmers' fields can be extremely high; for example, Conklin (1957) found that the Hanunoo people of Mindoro island in the Philippines planted more than 280 different types of food crops in their fields. After several rounds of crop planting, pests and weeds usually start to infest the area and soil fertility declines, and the field is left increasingly untended (Eyzaguirre, 1986).

Swidden farmers eventually leave the field to fallow. The ecological succession that subsequently takes place is site specific, but a transition from grasses to herbs to shrubs to woody species is common (Delang and Li, 2013). The accumulation of biomass in the regrowing vegetation helps to restore soil quality and structure, to suppress weeds, and to eliminate pests and diseases. This contributes to reducing the amount of labour input needed to eventually produce crops again (Padoch, 2018). Fallows also often feature a variety of useful plants and animals that swidden farmers harvest for food, construction materials, sale and medicine.

After the fallow period, which usually lasts for more than two years depending on the region, the area gets cleared again and the cycle continues (Padoch, 2018). Even though this describes the general life cycle of a swidden field, it is important to keep in mind that swidden agriculture is highly variable and exact practices differ from place to place (Conklin, 1961).

2.1.2.2 The environmental sustainability of swidden systems

The ecological productiveness and sustainability of swidden systems depend on multiple factors, including: (1) the control of soil erosion, (2) the limited accumulation of toxic compounds in the soil, (3) the replenishment of soil chemical nutrients removed by crop cultivation, and (4) the limited impact of weeds, disease and pests on crops (Bruun *et al.*, 2009; Ribeiro Filho *et al.*, 2015).

Worldwide, productive agricultural land has been lost as a consequence of soil erosion (Godfray *et al.*, 2010). In those areas where swidden farmers work, heavy rains are a main cause. Heavy rains can lead to soil saturation, causing the formation of free water on the surface and subsequently water runoff which causes soil to flush away (Gay-des-Combes *et al.*, 2017). Different components of swidden farming systems help to prevent this from happening. For example, manual cutting of vegetation limits soil erosion (Ehigiator and Anyata, 2011). Land is most susceptible to erosion when there is no vegetative ground cover. In swidden fields some tree species are usually left standing, and their roots can help to keep the soil in its place. Also the small size of swidden fields limits the potential for water runoff to gain speed (Kukla *et al.*, 2019).

Many swidden farmers farm on naturally acid soils, as this type of soil is widely distributed in tropical and subtropical regions. Acid soils are characterised by low amounts of nutrients and toxicity from metals such as aluminium, which do not favour crop growth (Bojórquez-Quintal *et al.*, 2017). The burning of fields can help reduce the acidity of soils, as ashes are highly alkaline and increase soil pH (Ohno and Erich, 1990). The increase in soil pH can subsequently increase the cation exchange capacity in surface soils, which reduces the levels of soluble and exchangeable aluminium, hence reducing the risk of heavy metal toxicity to crops (Bruun *et al.*, 2009). The burning of fields also improves the physicochemical properties of the soils (Kukla *et al.*, 2019). During the burning process, the biomass present on the field is converted into nutrient ash, which increases nutrients available to the soil. The amount of nutrients that gets added depend on the composition of the biomass burned and the intensity of burning (Bruun *et al.*, 2009). The effects on the soil are, however, short-lived. Nutrients such as nitrogen and carbon are lost in considerable amounts during the burning process (Demeyer, Voundi Nkana and Verloo, 2001), and nutrients which are retained in the ash such as potassium and phosphorus are at risk of being lost through leaching and erosion (Menzies and Gillman, 2003). Hence, there are limits to the extent ash fertilisation can sustain crop yields, especially in the long run (Gay-des-Combes *et al.*, 2017).

To replenish soils after a cropping period, swidden farmers rely on extensive fallow periods. During the fallow period, nutrients accumulate in the vegetation biomass and soil quality gets restored. It is important for the sustainability of the system that the fallow period is long enough for soil quality to recover. When the ratio of cultivation to fallow period increases, there is an increased risk of soil acidification and the loss of soil quality (Ribeiro Filho *et al.*, 2015).

Pests, including herbivores and seed-eaters, negatively affect the yields of crops worldwide (Oerke, 2006), including those of small farmers (Zou *et al.*, 2020). Major crop pests, including the fall armyworm (*Spodoptera frugiperda*) and the brown plant hopper (*Nilaparvata lugens*), often reduce the yield of small farmers (Wyckhuys and O'Neil, 2007; Willis, 2017; Zou *et al.*, 2020). To eliminate pests, swidden farmers usually rely on biotic pest control (Steward *et al.*, 2014). The level of biotic pest control in swidden fields depends on environmental factors, such as plant species, weather, field size, field age and crop species richness (Bianchi *et al.*, 2005; Wyckhuys and O'Neil, 2007; Maas *et al.*, 2015; Karp *et al.*, 2018). The composition of the wider landscape is also important. Forests and trees surrounding a field can provide important habitat for a range of fauna, including natural predators of crop pests, but also host crop pests (Tscharntke *et al.*, 2016). So whether surrounding non-crop habitat improves pest management may depend on the system and location involved (Karp *et al.*, 2018).

2.1.3 Challenging preconceptions

Small-scale agriculture has been the centre of debate with regards to food security and biodiversity conservation for decades. Already in 1957 the FAO wrote: 'Shifting cultivation, in the humid tropical countries, is the greatest obstacle not only to the immediate increase of agricultural production, but also to the conservation of the production potential for the future, in the form of soils and forests' (FAO, 1957). Also today, some argue that swidden agriculture is a particularly environmentally damaging form of agriculture, because it involves the cutting of trees and burning of fields (Padoch and Sunderland, 2013). Others say that it is a primitive form of agriculture as crop yields are relatively low, and that it may not be able to sustain today's growing populations (Padoch, 2018). Finally, some argue that swidden farming is a wasteful use of land as it involves the fallowing of fields after only a short cropping period (Padoch, 2018).

But beyond the smoke, it is clear that swidden agriculture plays a valuable role in agricultural production in forested regions (Padoch and Sunderland, 2013). Swidden cultivation is not necessarily destructive, but instead can contribute to a diverse and dynamic landscape with heightened biological diversity and productivity (Padoch, 2018). For example, the crop diversity within swidden fields themselves is generally high; swidden farmers often grow many different crop species, but also regularly maintain more than one variety (landrace) of crops for cultivation (Rerkasem *et al.*, 2009). In addition, the dynamic and cyclical nature of field management by swidden farmers creates a patchy and diverse landscape with vegetation in various stages of growth which can support local biodiversity (Rerkasem *et al.*, 2009; Padoch, 2018). Swidden farmers often do not just manage their own agricultural fields, but also collect wild foods from the surrounding natural habitat (Cruz-Garcia *et al.*, 2016). By selecting, cultivating and dispersing trees, palms and other perennial plants, swidden farmers contribute to the abundance of edible species in the forest (Flores and Levis, 2021). This has cascading effects on ecological interactions, with frugivores, for example, positively benefiting from the presence of fruits and seeds in the forests (Flores and Levis, 2021). Evidence is growing that when swidden cultivation is discontinued it is often replaced by intensified land uses such as sedentary agriculture, commercially driven large scale plantations or monocultures which have higher environmental impacts (Heinimann *et al.*, 2017). So swidden cultivation may be a valuable part of conservation landscapes (Padoch and Pinedo-Vasquez, 2010).

Swidden farming is also not necessarily primitive. For farmers who do not have access to resources such as inorganic fertilisers, pesticides and irrigation systems, swidden cultivation is more labour-efficient compared to alternative ways of farming and is thus a rational choice (Bruun *et al.*, 2009). Burning of fields remains one of the most efficient ways to replenish soils, clear debris and produce crops in tropical areas (Dressler *et al.*, 2020). Swidden systems have also been shown to be able to adapt to growing human populations and shrinking land availability by adopting the use of shorter but more intensively managed fallows (Cairns, 2007). Moreover, many swidden farmers play an active role in today's global economy by growing and selling cash crops, alongside their subsistence crops (Mertz, Padoch, *et al.*, 2009).

Furthermore, swidden farming is not necessarily wasteful. Fallowed fields are rarely truly abandoned. Instead, people return to them to harvest longer-lived food or cash crops and wild foods (Vira, Wildburger and Mansourian, 2015). Forest fallows also provide valuable ecosystem services, including pollination, pest control and water regulation (Padoch and Sunderland, 2013).

Finally, to many, swidden farming provides much more than a means of a livelihood; it is a way of life that is intertwined with people's culture and traditions (Pandey *et al.*, 2020). Thus, there needs to be a place and space for swidden agriculture in the 21st century.

2.2 Papua New Guinea

In PNG more than 75% of the population depends almost entirely on swidden agriculture for their daily food and livelihood (Conservation and Environment Protection Authority, 2019). Exploring how swidden farmers in PNG can navigate social-ecological changes is of crucial importance for the future of PNG and swidden farming.

2.2.1 National context

2.2.1.1 Geography, biodiversity and climate

The Independent State of Papua New Guinea is the largest Pacific island state. It is located just south of the equator, bound by the Bismarck Sea to the northeast, the Solomon Sea to the east, the Gulf of Guinea and the Coral Sea to the south, and Indonesia to the west. It consists of the mainland, four large islands and over 600 smaller islets and atolls, with a total area of circa 463,00 km^2. The country's geography is diverse and includes mountains reaching more than 4500 m elevation, tropical rainforests, valleys, wetlands and coral reefs (Bang, Poloma & Allen, 2003). The landscape continues to be formed as a result of tectonic collisions, with the Australian Plate colliding with the Pacific Plate as the dominant tectonic forces in the region (Tregoning *et al.*, 2000).

PNG contains half of the third largest area of tropical forest worldwide. In 2014, 71% of PNG's land mass was covered by some form of forest, including rainforest, mangroves, swamp forest and dry evergreen forest (Fig. 2.1). Rainforest is the dominant vegetation in PNG, and covers circa 60% of the country (Bryan and Shearman, 2014). PNG also lies within the Coral Triangle and has extensive fringing and barrier reefs. PNG's vast natural ecosystem hosts a unique range of biodiversity. It is estimated that the country is home to at least 2000 tree species, 150,000 species of insects, 314 species of freshwater fishes, 2800 species of marine fish, 641 species of amphibians and reptiles, 840 species of birds and 276 species of mammals, with many more species being yet unknown to science (Conservation and Environment Protection Authority, 2019). More than 30% of species are thought to be endemic to PNG (Conservation and Environment Protection Authority, 2019).

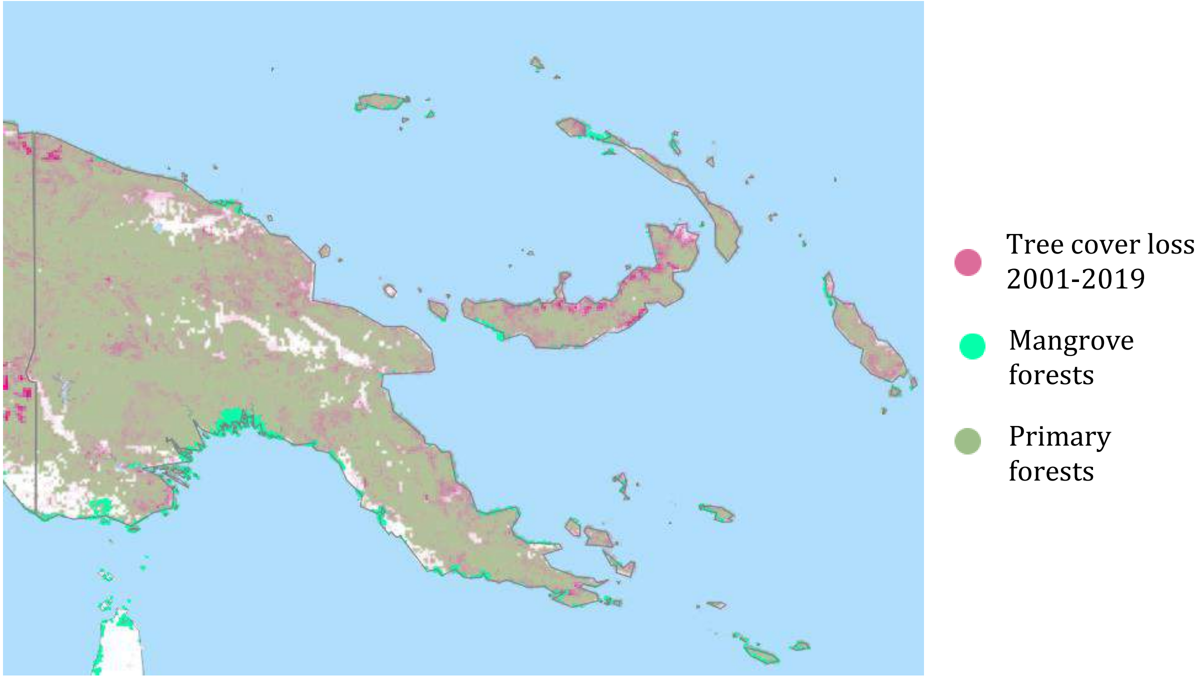

Figure 2.1 | Overview of primary forest cover in 2000 in dark green (Turubanova *et al.*, 2018) and mangrove forests in 2016 in light green (Bunting *et al.*, 2018) with tree cover loss from 2001-2019 displayed in pink (Hansen *et al.*, 2013). Accessed through Global Forest Watch on 01/03/2021 via www.globalforestwatch.org.

PNG has a tropical climate. The mean annual temperature is 27°C and is relatively stable from year to year. Altitude has the greatest influence on temperature, with temperatures falling at a regular rate of 0.5°C for each 100 m in altitude above 500 m (Bourke and Harwood, 2009). Regional patterns and seasonal cycles in rainfall, winds and ocean currents are mainly influenced by the Intertropical Convergence Zone (ITCZ), the West Pacific Monsoon (WPM) and the El Niño Southern Oscillation (ENSO) (Australian Bureau of Meteorology and CSIRO, 2011). The ITCZ is a persistent east-west band of converging low-level winds, rainfall and cloudiness (PACCSAP, 2014). It is strongest between April and October and corresponds to PNG's 'dry season'. The WPM is driven by large differences in temperature between the land and the ocean, and causes a reversal in the prevailing direction of the surface winds (PACCSAP, 2014). It prevails in PNG from November to March, and causes PNG's 'rainy season'. ENSO affects the strength and position of the ITCZ and the timing of the WPM. When ENSO is in its 'neutral' phase, the equatorial trade winds blow from east to west across the Pacific Ocean. They push warm surface water towards Asia, and in the east ocean temperatures are cooler due to upwelling which brings cold waters to the surface. In these conditions, weather patterns are relatively normal. However, usually every two to seven years, the trade winds change. During an El Niño, trade winds are weaker, the warm surface water moves eastward and ocean upwelling in the east is reduced, leading to warming of the surface temperatures of the central and eastern Pacific Ocean. During a La Niña, however, trade winds are stronger, and the pattern reverses (PACCSAP, 2014). Changing trade winds causes changes in rainfall patterns and temperatures across the globe, including PNG, for usually about a year. An El Niño in PNG can cause droughts, fires and frosts (Beauchamp *et al.*, 2019), whereas a La Niña results in wetter conditions and an increased likelihood of floods, landslides and cyclones (FAO, 2021a), with exact impacts varying by elevation. Both El Niño and La Niña have the potential to cause damage to food gardens and lead to crop losses (Beauchamp *et al.*, 2019; FAO, 2021a). From time to time PNG may also experience other extreme climatic events including tropical cyclones, storm surges, heat waves, drought and heavy rainfall (Australian Bureau of Meteorology and CSIRO, 2014).

2.2.1.2 The people of Papua New Guinea

PNG is currently home to 8.9 million people (The World Bank Group, 2020a). Between them they speak more than 800 languages, making PNG not only one of the most biodiverse but also linguistically rich countries in the world (Conservation and Environment Protection Authority, 2019). Tok Pisin is most widely spoken, and serves as the country's lingua franca. Over 95% of the population identifies as Christian, with Roman Catholic being the major denomination, followed by Evangelical Lutheran and Seventh Day Adventist (National Statistical Office, 2011). Many combine their Christian faith with traditional indigenous beliefs and practices (Street, 2010). The population is young with the median age being 22 years (United Nations, Department of Economic and Social Affairs, Population Division, 2019), and life expectancy at birth being 65 years (UNDP, 2020a).

Communities in PNG are traditionally structured around clans and tribes. A clan is normally a group of people united by descent from a common ancestor (Soukup, 2012), although what determines clan membership can vary widely across the country (Bourke and Harwood, 2009). The clan forms the major unit of social organisation in PNG, and is the primary unit for accessing customary owned-land and hereditary wealth (Hauck, 2010). Clans are usually led by a headman or council of elders, who also play an important role in allocating resources (Klopf, 2004). Often multiple neighbouring clans work together and form a tribe.

Eighty-seven percent of the people in PNG live in rural regions in small communities of a few hundred villagers (Oakland Institute, 2013; The World Bank Group, 2020a). People usually live with their 'wantoks', which translates to 'one-talks'. Even though the word 'wantok' was only formed with the development of Tok Pisin during the 1800s, its moral structure and spirit date back way before then (Nanau, 2011). Wantoks are groups of individuals who share a similar linguistic background, a common geographical area or an ethnic origin (Nanau, 2011), and often belong to the same clan or tribe (Baynes, Herbohn and Unsworth, 2017). They are bound together by the principle of mutual reciprocity, and are expected to take care of each other and jointly participate in socio-political, economic, traditional and cultural activities. The wantok system provides social support, but also comes with obligations to look after one's own group. It is an integral part of PNG's society.

2.2.1.3 Land tenure in Papua New Guinea

PNG operates a dual land tenure system; alienated land tenure refers to land that is owned by the state and accounts for circa 3% of land in the country, whereas customary land is controlled by tribes, clans and land groups and makes up circa 97% of PNG's land (Karigawa, Babarinde and Holis, 2016).

Customary ownership of land is recorded in local knowledge, believes and traditions. Local clan leaders delegate clan-owned land to individuals who can use it to, for example, build a house or establish an agricultural field (Baynes, Herbohn and Unsworth, 2017). Customary land tenure is relatively secure in PNG, as customary ownership is recognised by the country's constitution and customary land cannot be sold or leased to anyone besides other customary groups (Klopf, 2004; Anderson, 2010; Oakland Institute, 2013). However, local landowners do face a continuous threat that immigrant settlers or other clans may try to claim clan holdings (Baynes, Herbohn and Unsworth, 2017). In case of a dispute between local landowners, village courts or traditional 'peacemakers' can help settle the matter (Westermark, 1997).

Increasingly, the surface area under active customary land tenure is decreasing, and more land is managed by national and foreign corporate entities through a legal mechanism known as the 'lease-leaseback scheme' (Filer, 2012). In this scheme, groups of customary landowners lease some of their land to the government, which creates a formal title for the land and then leases it back to the same landowners or to persons or organisations of which they approve, for periods of up to 99 years (Filer, 2012). The scheme was created with the objective to enable customary landowners to register titles to their land and provide them with opportunities to enter into formal projects (Karigawa, Babarinde and Holis, 2016). However, there are concerns that the scheme is also used as a land grabbing mechanism, as leases may be granted to external entities by customary landowners under threat, bribery or intimidation, and without their free, prior and informed consent (Oakland Institute, 2013).

2.2.1.4 Papua New Guinea's economy

In 2019, PNG's per capita gross domestic product (GDP) was circa $2800, and was growing at around 6% per annum (The World Bank Group, 2019a). The economy is made up of two main components; a corporate-based sector and an agricultural sector (The World Bank Group, 2020c). The corporate based sector is mainly based on mining and the export of hydrocarbons, which together are thought to account for over 60% of PNG's GDP (Oxford Business Group, 2019). Within the mining sector, gold and copper are the sector's main outputs, followed by smaller amount of nickel and cobalt. In 2014, PNG launched the liquefied natural gas (LNG) project, operated by ExxonMobil, which has transformed PNG into a major exporter of hydrocarbons (ExxonMobil, 2021). While minerals and hydrocarbons dominate exports, agriculture engages most of PNG's labour force, although the majority of people are informally employed. The agricultural sector is thought to account for over 30% of PNG's GDP (Oxford Business Group, 2019). The main export crops are palm oil, coffee, cacao and copra (Bourke and Harwood, 2009).

2.2.2 Swidden agriculture in Papua New Guinea

2.2.2.1 A brief history of agriculture in Papua New Guinea

Around 50,000 years ago, the first settlers arrived in what is now PNG. They made a living from hunting, gathering and fishing, and they may also have managed nut-producing trees (Bourke and Harwood, 2009). By 10,000 years ago people in PNG started to practice agriculture, and in the years that followed crops including banana, sugar cane and sago were domesticated (Denham *et al.*, 2003; Bourke and Harwood, 2009). Around the same time, agriculture was also being developed in the Middle East and Central China (Bellwood, 2005). It is likely, though, that the development of agriculture in New Guinea was independent from what happened elsewhere (Denham *et al.*, 2003).

The colonial period of PNG shaped people's agricultural practices. By 1884, a British protectorate was declared over the south-eastern part of New Guinea, while the Germans claimed the north-eastern quadrant (Griffin, 1978) (Fig. 2.2).

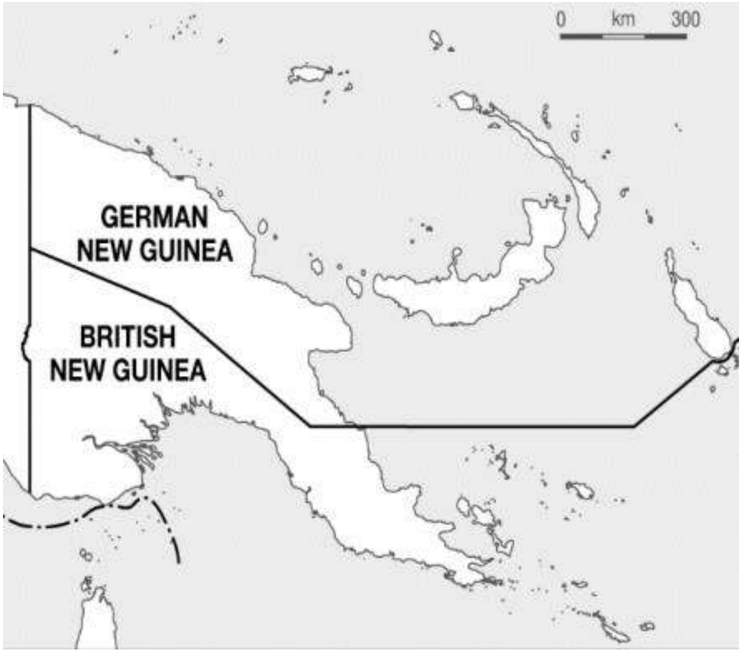

Figure 2.2 | Overview of which areas of PNG were claimed by the British and which by the Germans. Source: CartoGIS CAP Australian National University.

The colonisers introduced a wide range of crops to PNG, including cacao, coffee, rubber, tobacco and cotton (Bourke and Harwood, 2009). Plantations were also established, mainly around Madang and in the New Guinea islands. In 1906, Britain transferred their Territory to Australia. Australia invaded German New Guinea during World War I and took control of both territories. However, the two territories remained administratively separate until after World War II when they were united as the Territory of Papua and New Guinea (Griffin, 1978). Meanwhile, village agriculture was changing rapidly as a result of population growth, plant diseases and land alienation by colonial administrators to set up plantations. Village farmers started to adopt more productive crops, and the production of sweet potato and cassava expanded greatly. Farmers also started increasingly to integrate cash crops such as coffee and cacao into their food crop system (Bourke and Harwood, 2009). On September 16, 1975 PNG gained full independence from Australia (Griffin, 1978). The country became an independent state with a constitutional parliamentary monarchy, and has remained so. After the 1980s the plantation sector declined and smallholder farmers now dominate the production of all cash crops, except for palm oil (Bourke and Harwood, 2009).

2.2.2.2 Present-day swidden agriculture in Papua New Guinea

Nowadays, more than 75% of PNG's population depends almost entirely on swidden agriculture (Conservation and Environment Protection Authority, 2019). Swidden agriculture in PNG is practised from sea level to around 2800 m elevation, and farming practices vary from place to place. In general, a nuclear family (usually consisting of five to ten people, including children) will clear and burn up to three small primary or secondary forest areas around their village on land that belongs to their clan. The resulting fields are called 'food gardens' and form the basis of people's livelihoods (Fig. 2.3A-F). In these gardens a combination of food crops, such as sweet potato and banana, is grown. Increasingly, cash crops, such as coffee and cacao, are planted alongside food crops, and are mostly sold on informal markets (Bourke and Harwood, 2009). In addition, people may prepare a couple of small plots closer to their house where they mainly grow vegetables (Sillitoe, 1999). After 1-5 rounds of crop planting, gardens are usually left to fallow for 5-15 years before they are re-used again (Bourke and Harwood, 2009).

Many farmers also harvest fruits and vegetables in adjacent forests to complement their diets (Bourke and Harwood, 2009). Important forest tree crops include Highland kapiak (*Ficus dammaropsis* Diels), kumu musong (*Ficus copiosa* Steud.) and tulip (*Gnetum gnemon* L.). Forests are also used to hunt wild meat, collect building materials and firewood, find plant medicines, and provide spiritual value, among many other things (Bourke and Harwood, 2009).

How farming practices differ from place to place within PNG depends on many factors, including the local geography, climate, culture and population densities. In the Lowlands (< 600 m elevation), for example, swidden farmers tend to use long fallow periods, whereas in the Highlands, where population densities are highest, farmers use short fallows and incorporate plant material into the soil (Bourke and Harwood, 2009).

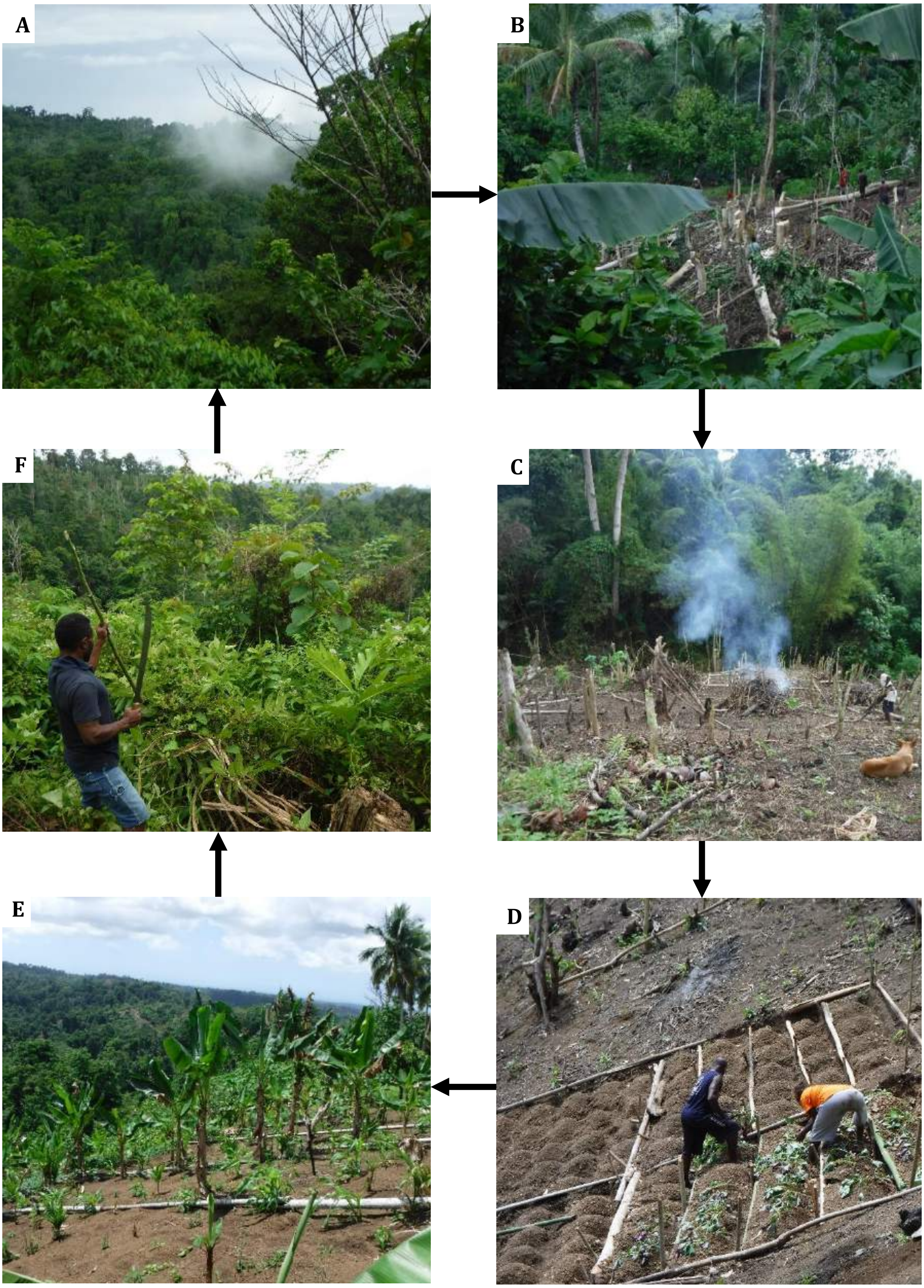

Figure 2.3 | Overview of the cycle of swidden farming in Ohu, PNG. Primary or secondary forests (A) get cut (B) and burned (C). Once the area is cleared, a variety of crops are planted (D), and farmers harvest from their food gardens (E). After a couple of rounds of crop planting, the area is left to fallow (F) and the forest regrows (A), until it is used again, and so the cycle continues.

2.2.2.3 Livestock in Papua New Guinea

About half of all households in PNG are engaged in some kind of livestock production (Glatz, 2017). Pigs are most often kept, usually in small herds consisting of one to twenty pigs (Bourke and Harwood, 2009). They are fed a combination of cooked sweet potato and cassava until they get sold, usually at informal markets (Glatz, 2017). After pigs, the most often kept livestock is chicken. Farmers usually purchase day-old hybrid boiler chicks in lots of 50 or 100 from a hatchery, and sell them when they are grown, mainly as live birds in local markets (Bourke and Harwood, 2009). Besides commercial purposes, both animal species also play an important role in customary practices. For example, pigs can be part of a bride price (West, 2006), and chickens can be exchanged during a funeral (Schram, 2007). Other livestock, including cattle, sheep, goats, ducks and rabbits are kept by only a small proportion of farmers in PNG (Bourke and Harwood, 2009).

2.2.2.4 Policy context with regards to agriculture in Papua New Guinea

In 2008, PNG's government started to develop a long-term vision, *Vision 2050*. The aim of *Vision 2050* was to reflect on the journey PNG has been on since gaining independence in 1975 and map out the country's vision for the next forty years (National Strategic Plan Taskforce, 2011). The mission set out in *Vision 2050* is for PNG to be a 'smart, wise, fair and happy society by 2050' and rank in the top 50 in the United Nation's Human Development Index (PNG is currently ranked 155) (National Strategic Plan Taskforce, 2011; UNDP, 2020b).

To help translate the aspirations set out in *Vision 2050* into practice, the PNG government has developed the Papua New Guinea Development Strategic Plan 2010-2030 (PNGDSP) (Department of National Planning and Monitoring, 2010). One of the main pillars of the PNGDSP is to grow the agriculture sector in PNG. Currently, PNG's GDP is mainly driven by the mining and energy sectors (see section 2.2.1.4). The government is keen to shift to an economy that is dominated by agriculture, forestry, fisheries, eco-tourism and manufacturing as the government believes that this will help in increasing household incomes across the population and with that enhance socio-economic performance (Department of National Planning and Monitoring, 2010). To grow the agriculture sector, *Vision 2050* and PNGDSP highlight the importance of increasing PNG's agricultural output and encouraging land reforms to bring customary lands into the formal sector (see section 7.4.3) (Department of National Planning and Monitoring, 2010; National Strategic Plan Taskforce, 2011).

The Department of Agriculture and Livestock (DAL) is the lead government agency responsible for the management of the agriculture sector in PNG. It has developed additional policies to implement *Vision 2050* and PNGDSP, including the Papua New Guinea National Food Security Policy 2018-2027, which outlines how food security for all Papua New Guineans can be ensured (Department of Agriculture and Livestock, 2018b), and the Papua New Guinea E-agriculture Strategy, which aims to harness available technologies in achieving PNG's agricultural goals (Department of Agriculture and Livestock, 2018a). The National Agricultural Research Institute (NARI) in PNG is responsible for providing technical, analytical, diagnostic and advisory services to the agriculture sector in PNG. NARI was established in 1996 under DAL but was brought under the Ministry of Higher Education, Research, Science and Technology in 2002 (National Agricultural Research Institute, 2011). The institute is well placed to contribute to and promote innovative agricultural development in PNG.

2.3 Study sites

The research presented in this thesis took place in collaboration with The New Guinea Binatang Research Centre (NGBRC), with most of the fieldwork being conducted along the Mount Wilhelm transect and in Ohu village.

2.3.1 The New Guinea Binatang Research Centre

NGBRC is an independent, non-profit organisation in PNG. The centre is devoted to training Papua New Guineans in biological research and conservation, advancing biological research in PNG, and setting up environmental education and nature conservation programmes (NGBRC, 2021).

NGBRC started off in 1997, following the abrupt closure of an American research station called the Christensen Research Institute (CRI) after an internal management dispute (Mervis, 1998). Five Papua New Guinean and two international researchers formerly based at CRI (including Prof. Vojtěch Novotný, now director of NGBRC), wanted to continue their research but had to look for alternative accommodation after CRI closed (Novotný, 2009). They managed to rent a house from the Lutheran Church in Nagada Harbour near Madang town, just across from where CRI was located, and the Parataxonomist Training Center (PTC) was founded. PTC was renamed to NGBRC in 2003 (Henning, 2014).

By now NGBRC has grown into a medium-sized organisation, featuring four buildings with dormitory-style accommodation, three well-equipped laboratories, a small library and multiple vehicles (NGBRC, 2021). NGBRC employs over 70 people. The core of the staff is formed by resident postgraduate students (studying for Honour's degrees, MScs and PhDs), permanent research staff and support staff. It is also a leading institution in para-ecologist training, in which people with a minimum level of formal education get trained to conduct biological research (Schmiedel *et al.*, 2016). Most members of staff live in or close to NGBRC's main station in Nagada Harbour, and from there they travel to the different field sites (Fig. 2.4). The Centre is overseen by a Board of Advisors, and managed by its director (currently Prof. Vojtěch Novotný) and associated director (currently Dr. Francesca Dem). NGBRC engages in collaborative research with national and overseas institutions. Researchers and students can visit NGBRC, make use of its facilities, collaborate with resident staff and students, and contribute to student training. Most collaborators are from the Czech Republic, USA, UK, Japan and Australia, but NGBRC welcomes researchers and students from anywhere (NGBRC, 2021).

Figure 2.4 | Location of NGBRC's main station highlighted in green in the Nagada Harbour in PNG. Photograph credits to NGBRC.

At the moment NGBRC is one of the most productive research centres in PNG (Nature Index, 2020). Its research is mainly focused on: (1) trophic interactions between plants, insects and vertebrates, (2) ecological factors that maintain the high biodiversity in tropical ecosystems, (3) elevational gradients in species diversity, and (4) the effect of habitat fragmentation, disturbance and climate change on biodiversity.

To conduct fieldwork necessary to answer NGBRC's main research questions, NGBRC collaborates with local communities in different parts of PNG (Fig. 2.5). Contact between communities and NGBRC is usually established via staff or by local communities reaching out to NGBRC. NGBRC's main research facilities include a 50-ha forest plot in Wanang, a 45 m tall canopy crane in the Kau Wildlife Area, and a complete elevational research transect along Mount Wilhelm (NGBRC, 2021).

NGBRC is aiming to combine research with biodiversity conservation, with research activities generating local employment and training opportunities which could be an incentive to local landowners for conservation. One successful example of this model is the Wanang

Conservation Area, where 10,000 ha of rainforest is being conserved despite the threat of logging (Novotny, 2010). NGBRC also supports village-based conservation areas in Baitabag (Kau Wildlife Area), Baiteta and Ohu (WIAD Conservation area), and works on developing new conservation areas (NGBRC, 2021) (Fig. 2.5).

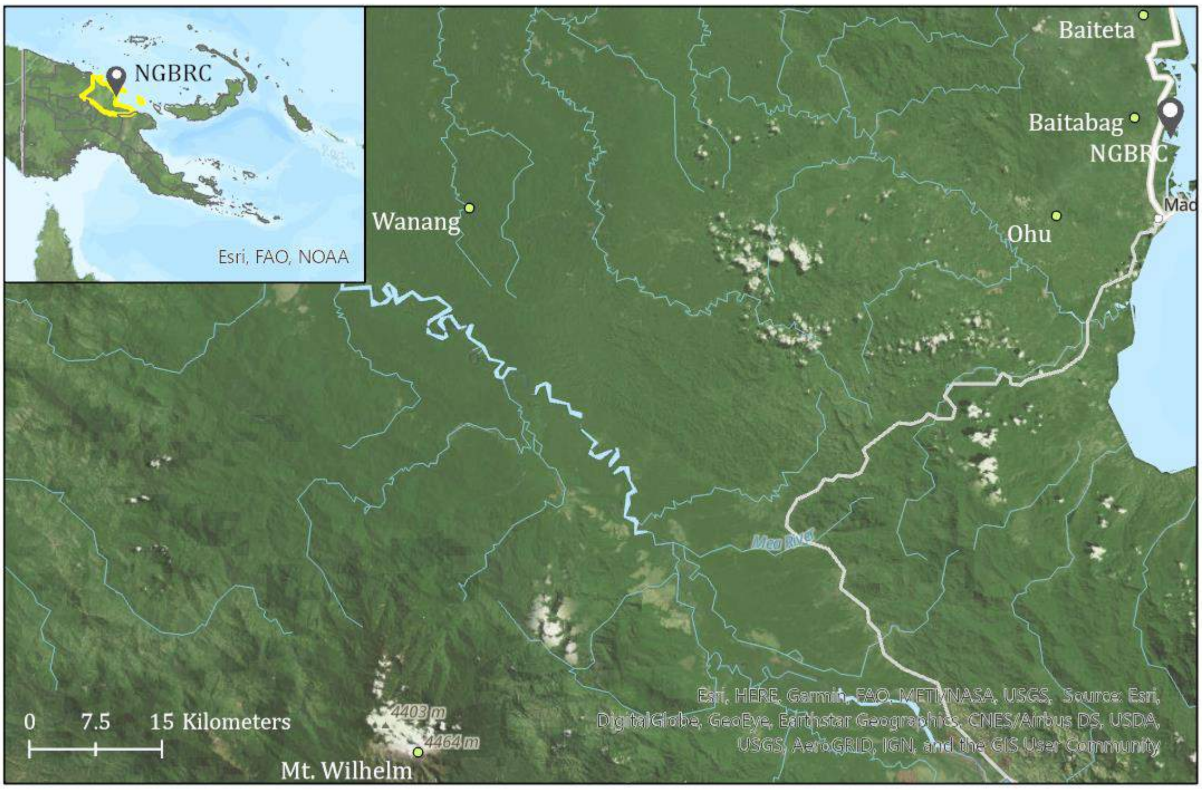

Figure 2.5 | Overview of the location of NGBRC in PNG, and NGBRC's main research sites in Madang province (highlighted in yellow in the top left map), including the Mount Wilhelm transect, Wanang, Baitabag, Baiteta and Ohu.

2.3.2 Mount Wilhelm transect

Chapter 3's study sites are located on a transect established by NGBRC along the slopes of Mount Wilhelm, as it allowed me to gain an understanding of how environmental factors such as elevation influence pest-related ecosystem services and disservices. Mount Wilhelm is located in PNG's Central Range and is the country's highest peak at 4509 m. The Mount Wilhelm massif is one of the most biodiverse areas in the world (Barthlott *et al.*, 2007), with almost a third of PNG's butterfly species and half of its bird species living on its slopes (Novotny and Toko, 2015). One of the reasons for this is that it comprises relatively pristine forest from sea level to the timberline, which is only disturbed in proximity to larger villages (Sam and Koane, 2014). The habitat on the mountain changes from Lowland alluvial forest (< 500 m), to foothill forest (501-1500 m) to lower montane forest (1501-3000 m) and upper montane forest (> 3000 m) (Sam *et al.*, 2019).

The Mount Wilhelm summit area above 3200 m is protected as the Mount Wilhelm National Park (Novotny and Toko, 2015). The rest of the area is owned and managed by local tribes. Communities along the north-eastern slope of Mount Wilhelm have partnered with NGBRC to establish research stations along an elevational transect ranging from 200 m to 3700 m (Middleton, Abdad, *et al.*, 2020). Landowners welcome visitors and can provide them with shelter, cooks, porters and field assistants (Fig. 2.6).

The villages along the transect are dispersed, and at least four different languages are spoken (Robillard *et al.*, 2017). A dirt road runs through the transect, but is only driveable by 4x4s and often impassable. Swidden agriculture remains the main livelihood (Middleton, Abdad, *et al.*, 2020).

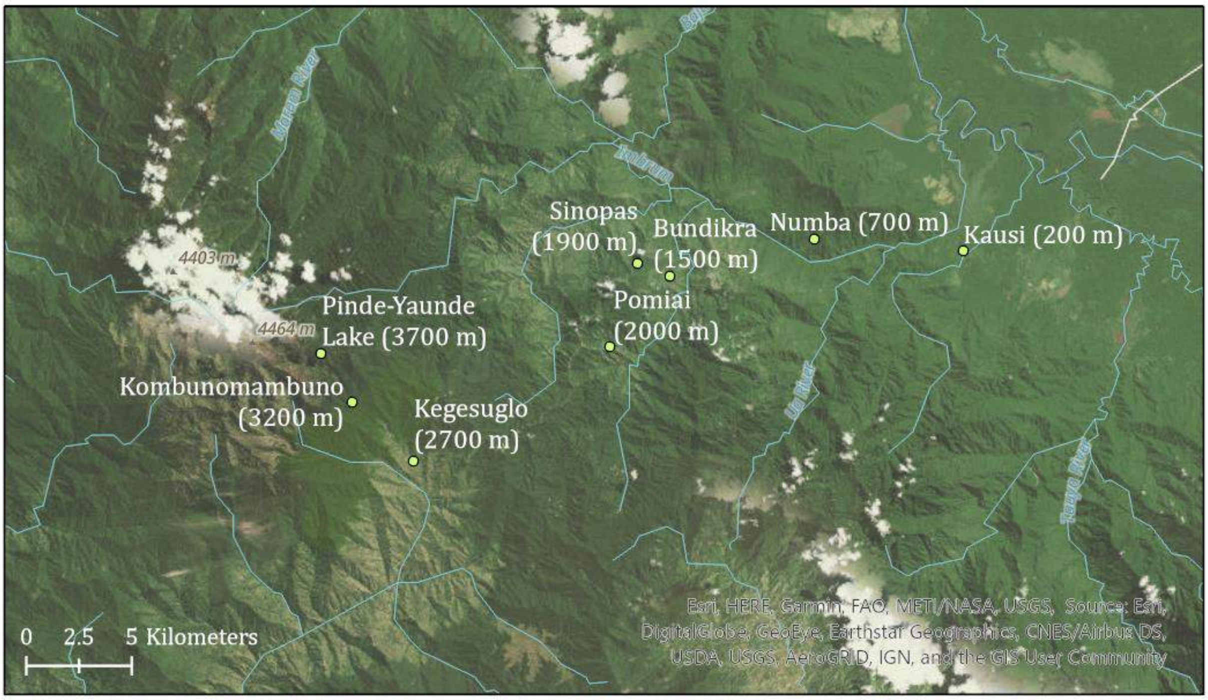

Figure 2.6 | Main research locations along the Mount Wilhelm research transect on the north-eastern slope of Mt. Wilhelm.

2.3.3 Ohu

Chapters 4, 5, 6 are based in Ohu, a village located circa 12 km west of Madang town, on the North coast of PNG at 150 m elevation. Spending a significant amount of time in one place allowed me to gain an in-depth understanding of swidden farming in this area. The average rainfall in the Madang area is circa 3600 mm, with a moderately dry season from July to September. Mean air temperature is 26.5°C and varies little throughout the year (McAlpine, Keig and Falls, 1983). Today, the village is made up of 11 clans belonging to three tribes. The vast majority of people in Ohu rely on swidden farming for their daily food and income. Farmers use clan-owned land for gardening, and grow a combination of food crops (such as banana and sweet potato) and cash crops (such as betel nut and cacao) (Hazenbosch *et al.*, 2021). The village settlements are surrounded by a mosaic of primary and secondary forests, which hosts significant biodiversity including the king-bird-of-paradise (*Cicinnurus regius*), lesser bird of paradise (*Paradisaea minor*) and rare birdwing butterflies.

In the 1950s, people in Ohu became concerned about declines in different species of bird of paradise, whose feathers they used for traditional dresses, festive dances and customary gift exchanges. Subsequently, four out of the 11 clans in Ohu came together and decided to prohibit hunting, mining, logging and gardening on part of their customary lands. This area is still being preserved today, and is now called the WIAD Conservation area. WIAD stands for Watup, Inamus, Asial and Dougu, and refers to the customary lands which are being conserved. Currently two of these clans are still actively involved in the management of the conservation area (Fig. 2.7).

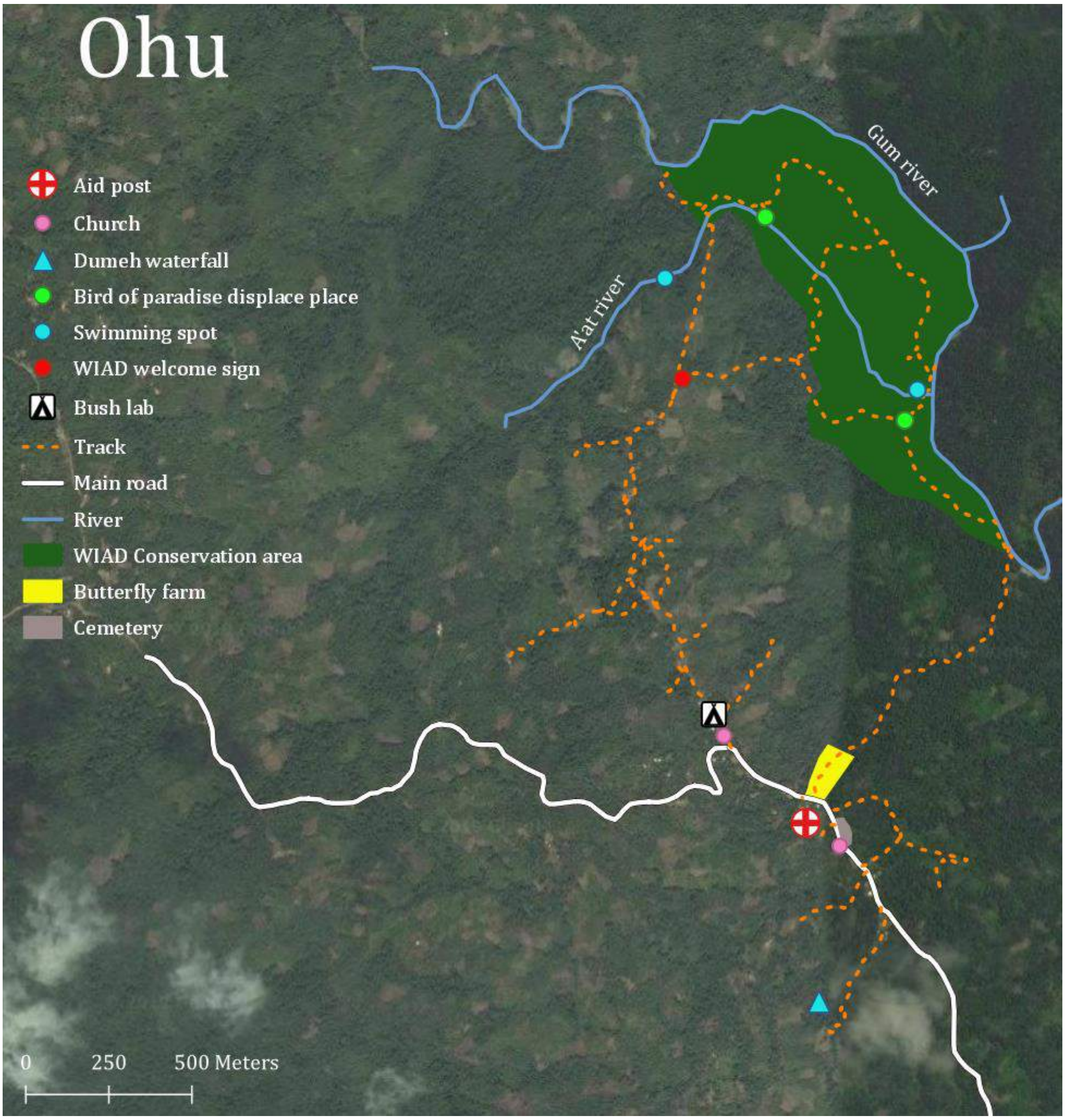

Figure 2.7 | Map of Ohu village and its most prominent features. This map was created and published with permission from Ohu's community leaders.

In 1992, a member of Ohu community, Hais Wasel, went to work at what used to be the Wau Ecology Institute (WEI) in Morobe Province. WEI was established in 1961 as a field station of the Bishop Museum in Honulu, but later became an independent environmental organisation involved in research and education in PNG (Mervis, 1998). Via Hais, different national and international scientists were introduced to Ohu, including researchers from CRI and later NGBRC.

In subsequent years, multiple projects based on Ohu's forests and biodiversity were established. For example, Hais founded the Ohu Butterfly Farm, which aimed to breed butterflies and sell part of them for commercial purposes (Weiblen and Moe, 2016). Brus Isua, another member of Ohu community, became the main research assistant of George Weiblen, an American researcher who collaborated with PTC and later NGBRC (Weiblen, 2005). In 1999 Brus set up the Ohu Bush Lab to support villagers, scientists and students to conduct research in Ohu without having to travel back-and-forth to NGBRC (Weiblen, 2005). Ohu Bush Lab features space for researchers to sleep and an area to work in (Fig. 2.8).

In the past and currently, national and international researchers are welcome to come to Ohu and stay in the Ohu Bush Lab to conduct their fieldwork, with logistics such as payments and transport usually arranged via NGBRC. These projects have brought some economic benefits, employment possibilities and educational opportunities to the village, with several members of Ohu village becoming full-time staff at NGBRC (Weiblen and Moe, 2016). It has also allowed Ohu to feature as a prominent field site in many scientific publications, e.g. Novotný and Bassett (1999), Sam *et al.* (2014) and Hazenbosch *et al.* (2021).

Figure 2.8 | Ohu Bush Lab (A) which allows national and international research to conduct fieldwork in Ohu village, PNG (B).

2.4 My research journey

During my BSc degree I was trained as a natural scientist. I had been taught how to objectify and quantify my research as much as possible. However, all research is embedded in the societies in which it takes place (Toomey, Knight and Barlow, 2017). This has long been recognised within the social sciences (Moon *et al.*, 2019), but I have come to realise that this is also true for the natural sciences. It is not often that natural scientists reflect upon how their gender, class, linguistic ability or religion may influence their production of knowledge (Ramesh, 2020). I do think it is very important to reflect on how you as a person and the society in which you operate may have influenced your production of knowledge as it allows the researcher to develop a sharper sense of reality and a more ethical orientation. I therefore reflect upon how my background and positionality may have impacted my research, both the more 'ecological' and 'social' work that I have done, how the social context may have impacted my work, and what ethical issues I encountered.

2.4.1 Arriving in PNG and Ohu

Most of my data collection took place in PNG. I arrived in PNG for the first time in January 2017 to join an ecological field survey, which formed the basis of the work presented in Chapter 3. The survey was part of a joint research project between NGBRC and the University of Oxford. After spending time at NGBRC's main base in Nagada Harbour, a team of NGBRC and University of Oxford researchers went to the Mount Wilhelm transect to start fieldwork (see section 2.3.2). I did not yet speak Tok Pisin, but people around me were keen to teach me. The very first sentence that a farmer from Kausi village taught me was 'graun blo yumi, em laif blo yumi' (which translates to 'our land is our life'). This surprised me as I was used to being taught how to count to ten or read the time first when learning a new language. It made me realise that to research farming in PNG was much more than just looking at crop production. Instead, it was looking into the very core of people's existence. I subsequently decided to focus the bulk of my research on one village in PNG, namely Ohu. Spending a significant amount of time in one place would allow me to better understand not only people's farms but their lives too, I believed.

A combination of historical, political and logistical considerations, rather than purely scientific reasons, made me to choose Ohu as my main study site for Chapter 4, 5 and 6. Ohu runs a village-based protected area called WIAD Conservation. A longstanding collaboration with NGBRC allows Papua New Guinean and international researchers to visit Ohu and WIAD Conservation (see section 2.3.3). When conducting my scoping trip in January 2018, Ohu's community leaders showed interest in my research project on swidden farming. The village was also relatively easy to access, which was useful for transporting all the required research materials. So Ohu seemed like a sensible choice. This research could, however, have taken place elsewhere in PNG as well, because questions about how swidden farmers can adapt to social-ecological changes are relevant across the country.

Once I had settled on Ohu as my main field site, I turned to planning my first fieldwork in the village. Results from the scoping trip showed that farmers in Ohu were most concerned with decreasing soil fertility and yields in their food gardens. Together with Shen, then a permanent member of staff at NGBRC, I designed the experiment presented in Chapter 4 to research how soil quality could be improved and yields increased. Shen grew up in a village close to Ohu, and so had intimate knowledge of the farming practices in the region. He had completed his Bachelor of Science in Forestry at the Papua New Guinea University of Technology in Lae, and was thus well placed to help design and conduct the experiment.

2.4.2 The effect of my background and social context on my ecological research in Ohu

In August 2018, Shen and I set off for Ohu to set up the experiment. Farmers in Ohu traditionally prepare their new food gardens in August, so it was a good time for setting up our experimental gardens too.

Given that all land in Ohu is customarily owned (see section 2.2.1.3), we had to negotiate with local farmers to find sites for setting up the experimental gardens. Brus, who is a village leader in Ohu but also works at NGBRC (see section 2.3.3), helped us find appropriate sites.

Historical, political and logistical considerations played a role when choosing the sites for setting up the experimental gardens. Two clans in Ohu (out of a total of 11 clans) own land within WIAD Conservation, and are thus most involved in facilitating NGBRC's work. Consequently, people from these clans expect to benefit most from any research project. When choosing sites for the experimental gardens, I was encouraged to mainly choose sites on the lands of these clans. The lands of these clans are representative of the land of neighbouring clans so there is no reason to assume that results were skewed. Nevertheless, it is clear that my ecological work was strongly influenced by the society in which it took place, despite my attempt to focus mainly on understanding environmental interactions.

I compensated landowners for using their land by hiring them as field assistants, following Brus's advice and NGBRC's guidelines on payment rates. I also returned all sweet potatoes harvested from the plots to the landowners after taking the necessary measurements. However, despite my best efforts, some people still challenged either myself, Shen or Brus by accusing us of not spreading the benefits of the project fairly. This is perhaps not surprising as most land in PNG is contested (see section 2.2.1.3), and disputes are more likely to arise when the stakes are higher. We navigated these challenges by careful negotiations, and managed to resolve the disputes and complete the experiment successfully.

2.4.3 The effect of my background and social context on my social surveys

Farming in PNG is a way of being (West, 2012), and it is influenced by social factors as well as by ecological factors (Conklin, 1961). So to fully understand the swidden farming system in Ohu, I had to dive into the social aspects of swidden farming too. So far most research that has been conducted in Ohu has been ecological work. My research project was one of the first times social surveys were conducted.

While designing the social surveys, I spent a lot of time talking to staff at NGBRC and Brus to understand what questions would or would not be appropriate or sensible to ask. I also piloted questionnaires in Baitabag, a village close to NGBRC's main station (see section 2.3.1), and adapted the surveys where necessary.

When starting my research I was aware that my presence as a white and international researcher in Ohu may have caused people to respond to me differently when conducting interviews, a phenomenon also called the 'research effect' (Tayeb, 2001). Especially in PNG, expatriates are often perceived as 'experts' with access to knowledge, which is regarded highly and may cause people to treat you differently (West, 2006). As a means of mitigating this, I decided to actively participate in village life with the hope that people would come to see me as more than an outside 'expert'. However, especially in the first few rounds of data collection, I decided it was better for staff from NGBRC to conduct the interviews. Many of the staff from NGBRC have worked in Ohu before (albeit on different and usually more ecologically focused research projects) and were aware of local customs, so were inevitably a more familiar presence for interviewees than myself. I tried, where logistically possible, to keep the research team as consistent as possible so that people would get to know us and feel comfortable speaking to us.

Every time before heading off to Ohu to commence data collection, I spent time with my research team from NGBRC to make sure we were all familiar with the interview protocols, knew how to ask interviewees for consent, administer the questionnaires appropriately and discuss possible translations of the questions from English to Tok Pisin. Many had some experience with social surveys before, but for some it was the first time they had conducted interviews. If that was the case, I made sure the person could first sit in on some interviews before starting to lead interviews him or herself. I made sure to employ both male and female staff or students from NGBRC so that women could be interviewed by women and men by men, if interviewees preferred this. Throughout the data collection process, I held regular feedback sessions with the research team to ensure that the interview protocols were working, and adapted where necessary. Especially in the beginning, the team from NGBRC functioned as a broker between myself and respondents, and I tried to incorporate their feedback and advice as much as I could.

By the time my team and I conducted the bulk of the interviews for Chapter 5 and 6, I had managed to master Tok Pisin to such a degree that I could easily understand and contribute to conversations myself. I had also spent more than a year working in Ohu, so people knew who I was and why I was there. At this point, I decided to become more involved in interviews myself so I could hear people's answers directly, but also to give respondents an opportunity to ask me questions if they wished so. From what I observed, interviewees appreciated me being more present later on so they had an opportunity to connect to me more directly.

All interviews were conducted in Tok Pisin, PNG's lingua franca (see section 2.2.1.2). However, in Ohu people also speak a local language called Amele. Given that most people in Ohu feel they can express themselves as well in Tok Pisin as in Amele, and that most staff at NGBRC speak Tok Pisin but not Amele, I thought it appropriate to conduct the interviews in Tok Pisin. For all interviews, we liaised with community leaders in Ohu to ensure they and their clan members were happy for us to conduct the interviews. The leaders were on stand-by when we conducted the interviews. Where necessary, they helped translate from Tok Pisin to Amele and vice versa, although there were only a couple of instances where this happened.

Before commencing any interview, my team and I gained the free, prior and informed consent of respondents. We did this by first explaining who we were, what the purpose of the research project in general (and the interview specifically) was, how we would ensure confidentiality of the data, and what people could do in case they wanted to raise a complaint. Following this, we allowed people to ask any questions or raise any concerns. If people were happy, we proceeded to ask for verbal consent to partake in the interview. I considered verbal consent appropriate due to the high levels of illiteracy in Ohu. After the interview we again gave people the opportunity to raise any questions or concerns. For the bulk of the interviews, I compensated people by sharing food and drinks with them. I decided not to provide financial payments, as the interviews were usually short (20-60 minutes) and monetary incentives may compromise free, prior and informed consent (Goodman *et al.*, 2004). Only for people who participated in the photography project in Chapter 6, did I provide financial compensation. This work took up multiple days so only providing food and drinks would not have been an appropriate compensation for people's time. As with the garden work, I followed Brus's advice and NGBRC's guidelines on how to best compensate people.

A challenging part of conducting social surveys was to ensure that the social surveys my team and I conducted were ethically appropriate. Of course, the research was approved by PNG's National Research Institute, and all interview protocols were deemed appropriate by the University of Oxford's Research Ethics Committee. However, as I was conducting my fieldwork, I realised that there was sometimes a disconnect between what was seen as ethically appropriate on an institutional level compared to what was deemed ethically appropriate by people in Ohu.

Sometimes, at an institutional level, protocols were approved without major reservations, but in reality the work would not have been ethically appropriate to carry out. For example, for Chapter 6, I originally planned on making participatory land use maps with different clans in Ohu. When conducting scoping interviews for a social survey on land use planning in Ohu, I came to realise that the social and governance situations were too complicated and potentially conflictual for this to be ethically appropriate on a local level. I consequently decided to focus the research for Chapter 6 on natural resource use, rather than on land use planning. So when conducting social surveys I had to set limits in terms of what was researchable to ensure it followed ethical guidelines and was also ethically appropriate on a local level.

Other times, at an institutional level ethical concerns were raised and practices to mitigate them enforced, but they did not necessarily align with what people in Ohu perceived as best ethical practices. For example, in Chapter 5, I report on the social network of four clans in Ohu. Following guidelines by the University of Oxford's Research Ethics Committee, I had an obligation to anonymise the data. I thus removed respondents' names and clan names from the network visualisation presented in Chapter 5. Despite this, I realised that those who are particularly familiar with the situation in Ohu may still be able to infer the identify of individuals based on the network visualisation in Chapter 5, because the network is so small. When discussing this issue with NGBRC, it became clear that people in Ohu may not share the need to anonymise their data.

On the contrary, they may have been disappointed that their names and clan names were removed. So what may be considered best ethical practices on an institutional level may be different to local perceptions of best ethical practices.

2.4.4 The effects of conducting interdisciplinary research

Being committed to conducting interdisciplinary research shaped the very research that I was doing, with observations from my ecological surveys feeding into my social surveys and vice versa. For example, by walking through the village while monitoring the different experimental gardens for Chapter 4, my team and I observed that some farmers were copying the practices that we were testing in the experimental gardens. This then led to the social survey presented in Chapter 5, in which I tracked and quantified the changes in farming practices and the social network. Similarly, hearing people speak about the history of their clan and resources in Chapter 6 helped me understand why people were farming in particular locations, and why yields in certain areas where higher than in others, as measured in Chapter 4.

Conducting interdisciplinary research also allowed me to improve the data quality from my social surveys; in most cases I was able to observe farmers after an interview, which helped me to understand how what I observed people doing corresponded with they said they did.

Overall, through conducting ecological and social surveys, and reflecting on the expected and unexpected things that happened during the research project, I have tried to sharpen my sense of reality and see beyond the smoke – the results of which you can read in this thesis.

- Chapter 3 -

Quantifying pest-related ecosystem services and disservices impacting smallholder agriculture along an elevational gradient in Papua New Guinea

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Measuring a food garden in Kausi, Papua New Guinea.

'Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning.'

- Albert Einstein

Abstract

1. Pests and their predators influence crop yields by mediating important ecosystem services and disservices in agricultural systems. To increase yields sustainably, farmers need to optimise ecosystem services and minimise disservices. However, for many smallholder famers in tropical countries there is a knowledge gap in how this is best achieved, because of a shortage of studies on these agricultural systems.
2. I quantified pest-related ecosystem services and disservices in food gardens of smallholders and surrounding forests (from which wild plants are harvested) in Papua New Guinea (PNG). I investigated how environmental factors including elevation, garden area, crop richness and garden age influenced pest damage and pest predation on different plant species.
3. The level of predation on insect herbivores (ecosystem service) was relatively high compared to previous levels reported in the literature, whereas the levels of seed disturbance and foliar herbivory (ecosystem disservices) were relatively low. Elevation had the greatest influence on pest-related ecosystem services and disservices, followed by differences between plant species and crop richness. Garden area and garden age did not have significant effects.
4. Current farming practices by smallholders in PNG, including establishing gardens close to forests, burning gardens at the start of the gardening season and planting a large variety of crops, are likely to enhance pest-related ecosystem services and reduce disservices. However, climate change and forest clearance threaten this positive balance, by potentially increasing the amount and activity of pests.
5. Monitoring ecosystem services and disservices contributes to building up a reliable evidence base for how small farmers can best harness ecosystem services, now and in the future.

3.1 Introduction

Ecosystem services and disservices play an important role in determining the yield of agroecosystems (Zhang *et al.*, 2007). Increasing ecosystem services and decreasing ecosystem disservices in agricultural fields can decrease the gap between actual and maximum attainable yields, reduce variability in this gap, and thus increase production (Bommarco, Kleijn and Potts, 2013). This is particularly relevant for smallholder farmers, who could benefit greatly from increased yields. Smallholders play an important role in national and global food security (IFAD and UNEP, 2013). They rely on localised areas (usually defined as two hectares or less) for their crop production, which provides the principal source of food and income for the family (Steward *et al.*, 2014). Smallholders may also collect wild foods from surrounding natural habitats frequently, especially in times of hunger (Cruz-Garcia *et al.*, 2016). There is a need to increase smallholder agriculture output because of rapid growth of the population in their areas (The World Bank Group, 2019b). Any increase will need to be achieved in the face of environmental challenges, including climate change, which may cause crop yields to decline (Wheeler and von Braun, 2013). Resources often used to reduce the yield gap, such as inorganic fertilisers and pesticides, may not be available to smallholders, may not be cost-effective for small farmers, and can have negative side-effects (Steward *et al.*, 2014; Zou *et al.*, 2020). Thus, optimising ecosystem services and minimising ecosystem disservices to maintain and increase yields in fields and their surroundings may be a more feasible strategy for smallholders (Bommarco, Kleijn and Potts, 2013; Zou *et al.*, 2020).

One of the most important ecosystem services affecting crops is biotic pest control (Zhang *et al.*, 2007). Pests, including herbivores and seed-eaters, have been estimated to decrease the yields of major crops worldwide by 8 to 15% (Oerke, 2006). On small farms, pests may have even more detrimental effects, with the rice yield of Chinese farmers being reduced with 20% due to pests (Zou *et al.*, 2020). Pests also greatly reduce plant growth and reproduction in natural systems, even if the amount of herbivory is as low as 2% (Crawley, 1985; Zvereva, Zverev and

Kozlov, 2012). Higher levels of pest control can reduce pest populations and lead to increased yields (Bommarco, Kleijn and Potts, 2013; Dainese *et al.*, 2019). The level of pest control in smallholder agricultural fields and their surrounding habitats is mainly affected by environmental factors, such as plant species, weather, field size, field age and crop species richness (Bianchi *et al.*, 2005; Wyckhuys and O'Neil, 2007; Maas *et al.*, 2015). The influence of wider landscape composition on pests and enemies can be highly variable across cropping systems and geographies (Karp *et al.*, 2018).

There is a knowledge gap in how smallholders can optimise pest-related ecosystem services and minimise disservices. Most research on biotic pest control has focused on large-scale farming in temperate regions, with few studies being conducted on tropical smallholder agricultural farms (Steward *et al.*, 2014). Biogeographic differences between temperate and tropical regions, in terms of species pools and climate, limit the between-biome generalisability of findings and thus management recommendations. Also, large-scale farming differs from smallholder farming in management intensity and landscape complexity, which may result in management interventions having different effects. Furthermore, most studies focus on the effect of pest-related ecosystem services on crops and ignore non-timber forest products, whereas wild foods are an important resource in smallholder-dominated landscapes (Cruz-Garcia *et al.*, 2016). In addition, ecosystem disservices caused by pests are poorly considered in the published literature, despite being an important consideration in the design of sustainable farming landscapes (Zhang *et al.*, 2007; Tschumi *et al.*, 2018). Finally, current patterns of pest-related ecosystem services and disservices may be affected by social-ecological changes, including climate and land use change (Tiede *et al.*, 2017). Quantifying pest-related ecosystem services and disservices in tropical smallholder agricultural systems enables us to understand whether and how farmers may further harness services and reduce disservices, and to explore how the current pattern of ecosystem services and disservices may be affected by future social-ecological changes (Bommarco, Kleijn and Potts, 2013; Karp *et al.*, 2018).

Here, I assessed the environmental factors that influence pest-related ecosystem services and disservices in a tropical smallholder agricultural system in Papua New Guinea (PNG). More than 75% of the population in PNG depends almost entirely on swidden agriculture, a type of smallholder agriculture, for their daily food and livelihood (Conservation and Environment Protection Authority, 2019). Swidden agriculture is practised from sea level to around 2800 m elevation in PNG, and farming practices vary from place to place. However, in general swidden farming in PNG involves a family (5-10 people, including children) clearing up to two small forest areas on clan-owned land surrounding their village each year. The resulting fields are called 'food gardens' and in them a combination of food and cash crops are grown. Farmers also harvest fruits and vegetables on a daily basis from selected plant species in adjacent forests to complement their diets (Bourke and Harwood, 2009). Usually, after 1-5 rounds of crop planting, gardens are abandoned and left to fallow for 5-15 years, before farmers return to these same plots (Bourke and Harwood, 2009). The highest human population densities on the mainland of PNG occur in the Highlands, between 1200 and 2800 m elevation. In these areas limited land is available to expand agricultural production (Fujinuma *et al.*, 2018), and therefore other approaches to increase yields are needed. On top of land shortages, climate change will influence agricultural production, although it is difficult to predict exact effects and how they will vary by elevation (Bourke and Harwood, 2009). In general, yields are likely to decrease due to a predicted increase in temperature of up to 1.1°C in 2030 relative to 1995 and an increase in the amount of rainfall, which will cause more heat and water stress to crops (Australian Bureau of Meteorology and CSIRO, 2014; The World Bank Group, 2021), and may also increase herbivory (Sam *et al.*, 2020).

There have been no previous studies of pest-related ecosystem services and disservices in similar systems where both crops and wild plants are harvested from adjacent habitats (Cruz-Garcia *et al.*, 2016; Dainese *et al.*, 2019). I had two objectives: (1) to quantify and compare pest-related ecosystem services and disservices on crops in food gardens and harvested wild plants in surrounding forests, specifically the predation of insect herbivores, seed disturbance and foliar herbivory, and (2) to assess which environmental factors, including elevation, garden area, crop species richness and garden age influence these ecosystem services and disservices. My aim was to provide a reliable evidence base that smallholders can use to identify adaptive strategies to harness pest-related ecosystem services and reduce ecosystem disservices, across a landscape of gardens and forests, which may contribute to achieving food security.

To address the first objective, I tested the hypothesis that the ecosystem service of pest predation would be relatively high in PNG compared to global estimates, because predation has been found to increase towards the equator and to be notably high in the tropics (Roslin *et al.*, 2017). I also expected pest predation to be higher on harvested wild plants in forests compared to crops in food gardens because pest predators often rely on natural habitat, which provides food sources, shelter and favourable microclimates (Kleijn *et al.*, 2019). However, pest predators can also contribute to ecosystem disservices by predating seeds which can cause reductions in the amount of seed available for germination (Setterfield and Andersen, 2018). I thus expected the ecosystem disservice of seed disturbance to also be relatively high (Ewers *et al.*, 2015), and to be higher in forests compared to food gardens. The average amount of foliar herbivory for wet tropical regions ranges from 11% for shade-tolerant species to 48% for gap specialists (Coley and Barone, 1996). I expected to find similar results in my study. Herbivorous insects often prefer crop habitats because of their high productivity, and thus I expected the level of foliar herbivory to be higher on crops in food gardens compared to wild plants in forests (Tscharntke, Rand and Bianchi, 2005).

To address the second objective, I tested the hypothesis that pest predation would be highest in small and crop-diverse gardens at low elevations. Smaller fields and higher vegetation diversity have been shown to enhance pest control (Bianchi, Booij and Tscharntke, 2006), and predators are more abundant at low elevations than at high elevations because of higher temperatures and more forest-like habitat (Sam, Koane and Novotny, 2015; Roslin *et al.*, 2017). However, because predators can also contribute to eating and removing seeds, I expected seed disturbance to decrease with increasing elevation, and to be higher in smaller and more diverse food gardens. Previous research has shown a variety of patterns of foliar herbivory along elevational gradients, including decreasing, increasing, constant and hump-shaped patterns (Moreira *et al.*, 2018). A study in the same area in PNG found that *Ficus* herbivory peaked at 700 m and decreased towards the Lowlands and higher elevations (Sam *et al.*, 2020). I expected to find similar results in my study, albeit on different plant species. Finally, I tested the hypothesis that the level of foliar herbivory would be higher in bigger, older or less diverse gardens because of increased pest pressure (Bianchi, Booij and Tscharntke, 2006).

3.2 Materials and Methods

3.2.1 Study site

Data were collected in six villages, Kausi, Numba, Bundikra, Sinopas, Pomiai and Kegesuglo, chosen because they are located along an elevational gradient from circa 200 m to 2700 m. The villages lie along the slopes of Mount Wilhelm, which is in the Central Range of PNG (Fig. 3.1). The temperature along the gradient decreases linearly by approximately 0.54°C for each 100 m in altitude, and during the fieldwork the temperature dropped from a mean of 26.5°C at 122 m to 10.8°C at 2950 m. Average annual precipitation was 3509 mm at 122 m and 3347 mm at 2950 m (Shearman, unpublished). The forests were mostly undisturbed and changed from Lowland alluvial forests (< 500 m) to foothill forests (501-1500 m) to lower montane forests (1501-3000 m) (Sam *et al.*, 2019). Only at Sinopas did the forests contain open areas and smaller trees because of human disturbance. Fieldwork was conducted during the wet season between January 24th and March 15th, 2017.

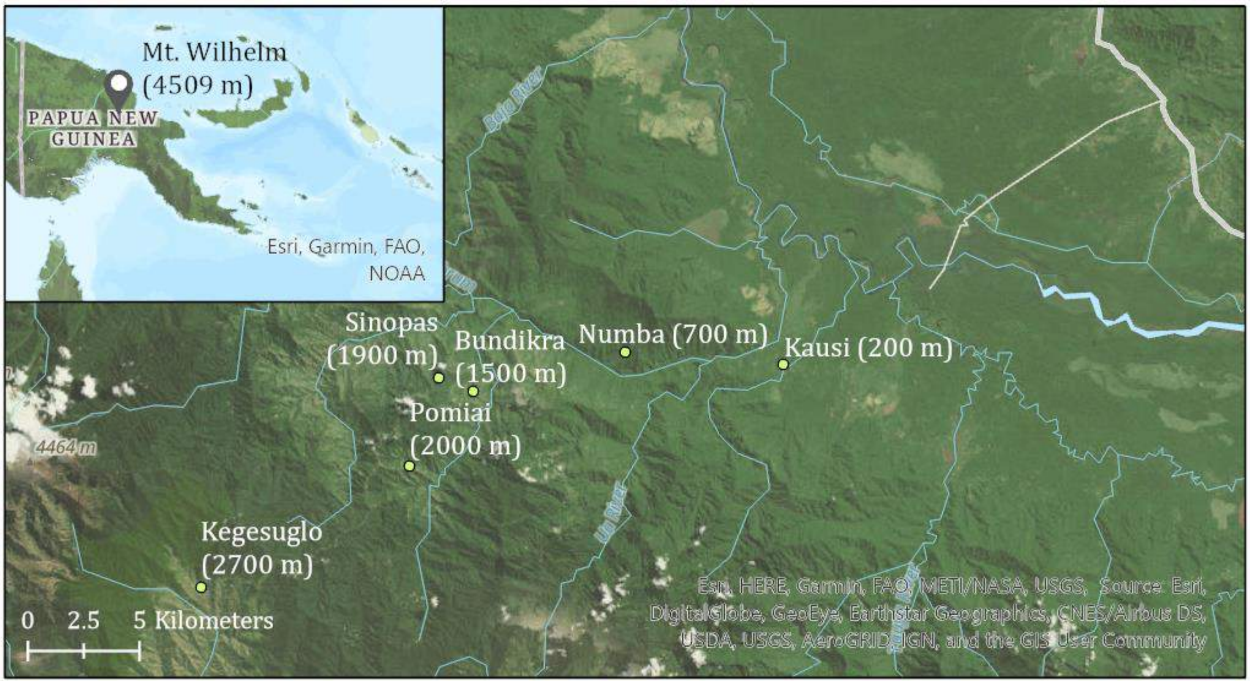

Figure 3.1 | Geographic locations of the study sites along the Mount Wilhelm transect in PNG.

Measurements of ecosystem services and disservices were taken in 69 food gardens (10-13 gardens per villages), and in six forest areas adjacent to food gardens in each village. The research team took measurements in gardens in which they were allowed to work, and that varied in age, size and crop richness, as per the hypotheses. All gardens were in close proximity of the forests. In order to respect cultural norms, community leaders were asked to select food gardens. None of the gardens were treated with pesticides. A pilot study was carried out in 2016 to assess the crop species planted across the elevational gradient (Ibalim, Bau and Tulai, 2016). From this, the seven most commonly planted crops were selected and on them measurements were taken. They included banana (*Musa* spp.) cultivars, cassava (*Manihot esculenta* Crantz), chayote (*Sechium edule* (Jacq.) Sw.), Chinese taro (*Xanthosoma saggittifolium* (L.) Schott), sugarcane (*Saccharum officinarum* L.), sweet potato (*Ipomoea batatas* (L.) Lam.) and taro (*Colocasia esculenta* (L.) Schott). Care was taken to not damage the food gardens, and garden owners were compensated appropriately. Measurements in forests were taken from Highland kapiak (*Ficus dammaropsis* Diels), kumu musong (*Ficus copiosa* Steud.) and tulip (*Gnetum gnemon* L.). These are naturally occurring tree species which are often harvested for food. Tulip is also used to make string bags called 'bilums' , which are commonly used in PNG (Bourke and Harwood, 2009).

3.2.2 *Measuring pest-related ecological services and disservices*

Ecosystem services (predation of pests) and disservices (seed disturbance and foliar herbivory) were measured in food gardens and adjacent forests (Appendix A, Table 1) using well-established methods (Ewers *et al.*, 2015; Roslin *et al.*, 2017; Sam *et al.*, 2020).

3.2.2.1 *Predation of insect herbivores*

To assess the activity of predators of insect herbivores, including birds and ants, artificial caterpillars were placed in haphazard locations on leaves of each of the focal plant species. This method has been widely used to estimate predation on insect herbivores (Howe, Lövei and Nachman, 2009; Sam, Koane and Novotny, 2015). In each garden, 20 artificial caterpillars per crop species were set out with a minimum distance of 40 cm between them. One hundred artificial caterpillars per wild plant species were set out in the forests surrounding each village. Artificial caterpillars were made from modelling clay. The clay was pressed through a syringe to ensure a smooth surface so that damage could easily be identified (Sam, Koane and Novotny, 2015). Artificial caterpillars were green and 15 x 3 mm in size, matching the median body size of caterpillars in PNG (Novotný and Basset, 1999). Based on results from a pilot study (Ibalim, Bau and Tulai, 2016), I recovered the artificial caterpillars after 24 hours. Each caterpillar was carefully examined for bite marks from insects, rodents or birds (Low *et al.*, 2014), and the proportion of attacked and unattacked caterpillars was calculated. If caterpillars had bite marks from two distinct categories of predators they were counted as two attacks. The category of predator was not taken into account since my focus was on quantifying predation of insect herbivores. Henceforth, the word 'predation' will refer to the proportion of artificial caterpillars attacked.

Muchula *et al.* (2019) warn that the thermal properties of plasticine may make it an unsuitable substrate for prey models, because at higher temperatures plasticine is softer which increases the likelihood of marks becoming visible. However, they also show that under field conditions when temperatures are between 16°C and 32°C the effect of temperature on plasticine is not significant (Muchula, Xie and Gurr, 2019). In my study site the temperature dropped below 16°C at 2075 m elevation, therefore I made sure to interpret any differences in attack below 2075 m compared to with above 2075 m with care.

3.2.2.2 Seed disturbance

Seed disturbance (defined as seeds eaten, partly eaten or removed from the experimental site) was quantified experimentally following a method described by Ewers *et al.* (2015). Ewers *et al.* (2015) found that large seeds were not disturbed by invertebrates, while small seeds were ignored by vertebrates, so I used two different seed sizes to capture seed disturbance by both vertebrates and invertebrates. The same two species of seeds were used for all measurements so that I could compare disturbance across crops and elevations. For each of the focal plant species, a pile of 20 large cacao seeds was placed underneath each of the focal plant species, and a pile of 20 small sesame seeds 30 cm away. Seeds were placed on the ground on top of a leaf of the focal plant species. After 24 hours the number of disturbed seeds was counted separately for cacao and sesame seeds, and the proportion of disturbed versus undisturbed seeds was calculated. I expected large cacao seeds to be mainly disturbed by vertebrates including birds and small mammals, and the small sesame seeds to be primarily attacked by invertebrates including ants (Ewers *et al.*, 2015). Seeds were set out in both gardens and forests in four to ten locations per plant species per village. In gardens two seed stations were set up per crop species, and the mean number of disturbed seeds was calculated to avoid pseudo-replication.

3.2.2.3 Foliar herbivory

To measure foliar herbivory on crops, garden owners were asked to collect 10 leaves from 10 different individuals per plant species. Garden owners were specifically asked to collect a range of leaf types including young and old leaves, and damaged and undamaged leaves to ensure a stratified random sample. In forests the research team collected leaves, again including both young and old, and damaged and undamaged. Leaf petioles were cut off and put on a 50 x 50 cm frame with a white background. A leaf frame was prepared for each individual plant species per garden and forest location. Leaf frames were photographed with a 16.0 megapixel camera (Nikon Coolpix AW130). Leaf areas were estimated using ImageJ 1.51j8v (Schneider, Rasband and Eliceiri, 2012). The amount of foliar herbivory was calculated by subtracting the total leaf area excluding holes, from the total leaf area including holes. This is a well-established method to measure foliar herbivory (Sam *et al.*, 2020). Herbivorous insects are most active during the season in which fieldwork was conducted, so estimates of foliar herbivory may be at the high end of the range for PNG (Sam *et al.*, 2020).

3.2.3 Recording predictor variables

For each food garden Global Positioning System (GPS) coordinates, garden area, food crop richness and garden age were documented. GPS coordinates (including elevation) were recorded with a Garmin GPSMAP 64st. The size of a food garden was measured with a GPS by walking around the edges and calculating the area in m^2. Crop richness was measured by counting the number of crop species in each food garden. Gardens in PNG are often intercropped with a large variety of crops, so crop richness rather than crop abundance best characterises swidden farmers' gardens. Garden age was estimated in years by the garden owner, and validated by looking at the maturity of the crops. For wild plants in forests, only GPS coordinates of the sampling location were recorded as the other variables were not relevant.

3.2.4 *Statistical analyses*

All statistical analyses were done in R version 4.0 (R Core Team, 2020). For all models, collinearity between independent variables was tested calculating the variance inflation factor using 'vif' from the car package (Fox, Weisberg and Price, 2018).

To investigate the influence of predictor variables on the predation on artificial caterpillars and the disturbance of large or small seeds in gardens, a generalised linear model with a binomial error structure was fitted to the data with the ratio of attacked to unattacked caterpillars or seeds as the dependent variable, and crop type, elevation, garden area, crop richness and garden age as the independent variables. The ratio was calculated using the 'cbind' function from the base package. For foliar herbivory in gardens a similar model was fitted, but a beta distribution was used as foliar herbivory was recorded in percentages, using the 'gamlss' function in the gamlss package (Stasinopoulos *et al.*, 2020). I expected a hump-shaped pattern of foliar herbivory across elevation a priori and thus I added $elevation^2$ as an independent effect in the case of foliar herbivory. Data from forests were analysed separately and only elevation and plant type were included as independent variables (Appendix A, Table 2). Multiple comparisons between plant species were done using 'glht' from the multcomp package, which adjusts p-values for multiple comparisons (Hothorn, Bretz and Westfall, 2019).

I directly compared the level of predation, seed disturbance and foliar herbivory between gardens and forests, including elevation and habitat (forest or garden) as independent variables and the level of ecosystem (dis)service as dependent variable. Since I measured different plant species in different locations, any differences could be species-specific rather than habitat-specific, therefore results must be interpreted with this in mind.

For count data I checked whether over-dispersion occurred by calculating the ratio between residual deviance and degrees of freedom. If the ratio was >1.2 the model was re-fitted with a quasi-binomial distribution. I report values from the full models because I only included a few unrelated independent variables, and thus it was not necessary to simplify the models. Means ± standard errors (s.e.) are shown.

3.3 Results

3.3.1 Study site attributes

Food gardens had a mean area of 768 ± 80 m^2 (range 133 to 3000 m^2) and mean age of 2.7 ± 0.17 years (range one to seven) (Appendix A, Table 3). Across the elevational gradient, 49 crop species were recorded in the studied gardens, and 97 crop species across a wider sample (Appendix A, Table 4). The mean number of crop species per garden was 13 ± 0.41 (range six to 21); Numba (756 m) and Bundikra (1471 m) had the highest number of crop species per garden. Of the seven focal crops, sweet potato was the only one planted in large amounts along the entire gradient (174-2669 m). Most crops were planted mainly at low to mid elevations (banana, Chinese taro, sugarcane: 174-1954 m, cassava 174-1471 m), while taro and chayote were found at mid-elevations (756-1954 m). Of the wild species, tulip occurred at low elevations (188-703 m), kumu musong low to mid-elevations (188-1752 m), and Highland kapiak at high elevations (1443-2685 m) (Appendix A, Table 3).

3.3.2 Quantifying pest-related ecosystem services and disservices

3.3.2.1 Predation of insect herbivores

The proportion of artificial caterpillars attacked in gardens ranged from 14 ± 1.8% at 135 m elevation to 0% at 2742 m, and in forests from 17 ± 0.50% at 188 m to 0% at 2685 m (Appendix A, Table 5-8). There was no significant difference in predation between gardens and forests (Table 3.1).

Predation in gardens significantly decreased as elevation increased. Predation was not significantly affected by crop plant, garden area, crop richness or garden age (Table 3.1). In forests, predation also significantly decreased as elevation increased (Fig. 3.2A), and did not differ among wild plant species (Appendix A, Table 9).

3.3.2.2 Seed disturbance

The proportion of large cacao seeds disturbed in gardens ranged from 17 ± 12% at 148 m elevation to 2.5% at 2681 m, and in forests from 1.0 ± 0.78% at 188 m to 0% at 2685 m. For small sesame seeds the proportion of disturbed seeds in gardens ranged from 68 ± 14% at 148 m to 58% at 2681 m, and in forests from 84 ± 6.7% at 188 m to 57 ± 11% at 2685 m (Appendix A, Table 5-8). Seed disturbance was significantly higher in forests compared to gardens for small seeds, but not for large seeds (Table 3.1).

Disturbance of large seeds in gardens decreased significantly with elevation. For small sesame seeds, however, disturbance significantly increased as elevation increased, and also increased with higher crop richness. Disturbance of both large and small seeds was not affected by crop type, garden area or garden age (Table 3.1). In forests, disturbance of large seeds was not affected by wild plant species or elevation (Fig. 3.2B). For small seeds, however, disturbance was significantly higher for Highland kapiak than for kumu musong, and decreased as elevation increased (Fig. 3.2C) (Appendix A, Table 9).

3.3.2.3 Foliar herbivory

Mean foliar herbivory in gardens ranged from 0.78 ± 0.39% at 131 m elevation to 0.089% at 2742 m, and in forests from 4.6 ± 1.1% at 155 m to 0.080 ± 0.039% at 2685 m, but peaked at 700 m (Appendix A, Table 5-8). Foliar herbivory was significantly higher in forests compared to gardens (Table 3.1).

Foliar herbivory in gardens was not affected by crop species, elevation, garden area, crop richness or garden age (Table 3.1). In forests foliar herbivory differed significantly between wild plant types with Highland kapiak having significantly lower levels than kumu musong. The level of foliar herbivory in forests showed a hump-shaped pattern, increasing up to 700 m elevation and subsequently decreasing (Fig. 3.2D) (Appendix A, Table 9).

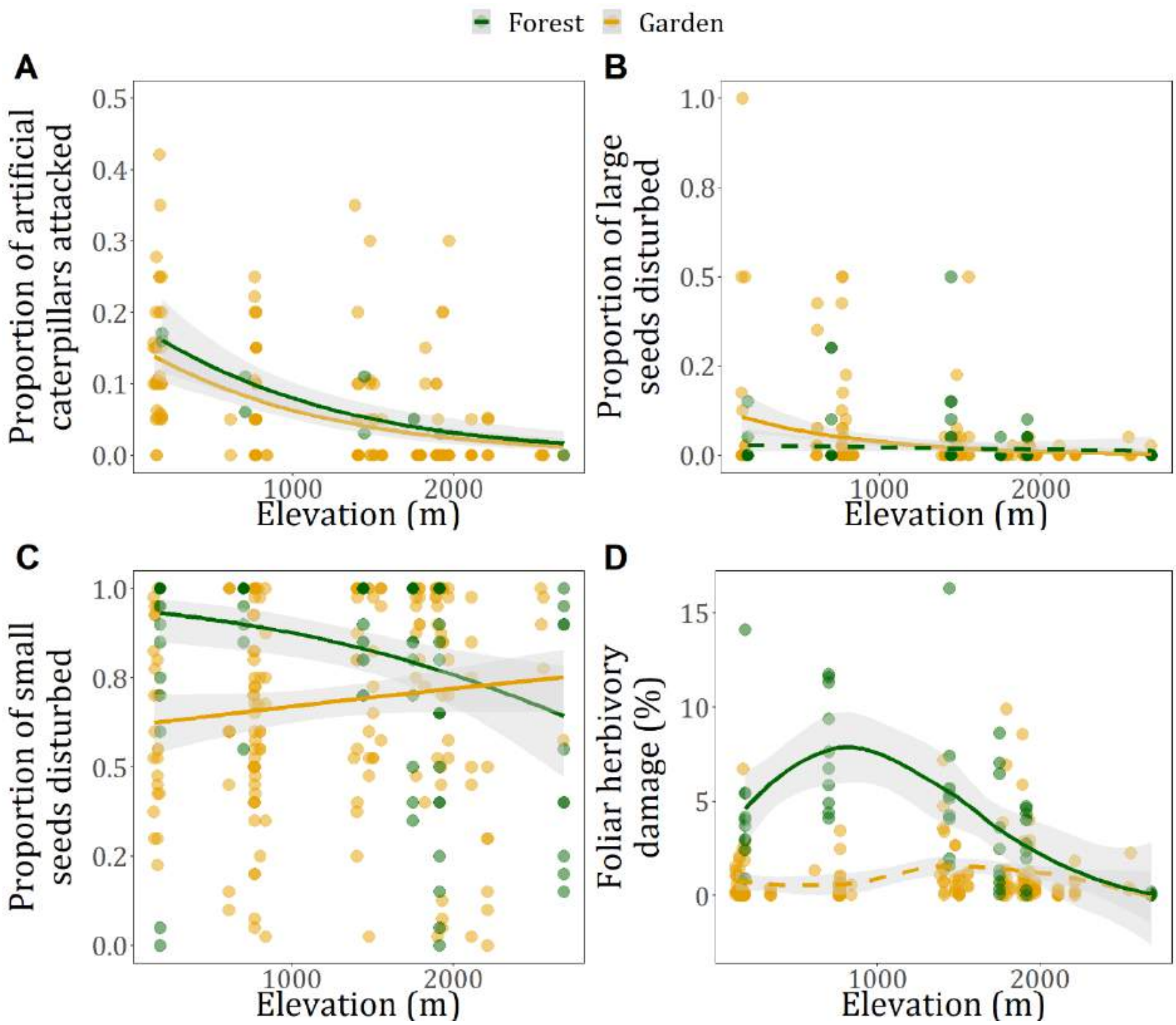

Figure 3.2 | Elevational patterns of the studied ecosystem services and disservices. Yellow symbols and lines indicate gardens, green symbols and lines forests. Solid lines illustrate statistically significant relationships at $p < 0.05$, dashed lines non-significant relationships. Note that for artificial caterpillars (A), large seeds (B) and small seeds (C), proportions rather than weighted ratios (as used in the statistical analyses) are plotted for simplicity. The lines for the amount of foliar herbivory (D) are plotted using local polynomial regression fitting.

Table 3.1 | Summary of the model results from comparisons between gardens and forests, and from within gardens and forests. Here I display only the variables of interest. For full results, see Appendix A, Table 9. ns = non-significant, +/- = $p < 0.05$, ++/-- = $p < 0.01$, +++/--- = $p < 0.001$, with + indicating a positive effect and - a negative effect.

Response variable	Gardens vs. forests		Plant type	Elevation	Elevation^2	Garden area	Crop richness	Garden age
Predation of insect herbivores	ns	*Gardens*	ns	---		ns	ns	ns
		Forests	ns	--				
Seed disturbance – large seeds	ns	*Gardens*	ns	--		ns	ns	ns
		Forests	ns	ns				
Seed disturbance – small seeds	+++ Gardens < forests	*Gardens*	ns	++		ns	++	ns
		Forests	- Highland kapiak > kumu musong	--				
Foliar herbivory	+++ Gardens < forests	*Gardens*	ns	ns	ns	ns	ns	ns
		Forests	+ Highland kapiak < kumu musong	+	--			

3.4 Discussion

This work quantified current pest-related ecosystem services and disservices for swidden agriculture along an elevational gradient in PNG, and investigated how they are influenced by environmental factors.

3.4.1 Predation of insect herbivores

Previous research in the same area found that in the Lowlands the percentage of attacked caterpillars was 14% (Sam, Koane and Novotny, 2015) which is similar to my result, but relatively high compared to global estimates of predation (Roslin *et al.*, 2017), as I hypothesized. I expected predation to be higher in forests. However, I found predation in food gardens to be similar to those in forests. Although in this study I did not distinguish attacks by different taxa, insectivorous birds and ants are the most important predators in this system, and my estimate of predation was very likely largely determined by their combined effect (Mooney, 2007; Sam, Koane and Novotny, 2015). Food gardens in PNG have a complex vegetation structure with many different growth forms, which may have attracted insectivorous birds as has been shown in cacao plantations in Indonesia by Clough *et al.* (2009), and ants as shown in coffee plantations in Costa Rica by Perfecto and Snelling (1995).

As elevation increased, predation decreased, similar to what Sam, Koane and Novotny (2015) find. Ants are generally thermophilic, thus their abundance is expected to decrease as elevation increases (Plowman *et al.*, 2017), which may have contributed to a decrease in the observed predation. Birds, on the other hand, are endothermic and the abundance of insectivorous birds along the Mount Wilhelm gradient shows a mid-elevational peak (Sam, Koane and Novotny, 2015). However, the biomass of insectivorous birds decreases along the gradient which may explain the lower attack rate higher up the mountain, because smaller birds eat fewer insects (Sam *et al.*, 2019).

3.4.2 Seed disturbance

Seed disturbance showed a varied picture depending on habitat, elevation and crop richness. Large seeds have been shown to be mainly attacked by vertebrates including birds, and small seeds by invertebrates including ants (Ewers *et al.*, 2015), and this corresponds to observations in the field (Yalang, personal observation). The disturbance of large seeds in my study was low compared to Ewers *et al.*'s (2015) findings from both primary and logged tropical rainforest in Borneo, whereas for small seeds the disturbance in the forests was similar to Ewers *et al.* (2015). This indicates that within tropical systems ants may be major agents of resource removal, in agreement with Griffiths *et al.* (2018). Disturbance for large seeds did not differ between gardens and forests, which again indicates that vertebrate predators effectively colonise gardens. Disturbance of small seeds, however, was higher in forests compared to the gardens, which may be because the abundance of ants may be higher in forests compared to gardens, although further research would need to confirm this.

There was an elevational decline in the disturbance of large seeds in gardens. This may have been due to a decrease in frugivorous birds with increasing elevation (Sam *et al.*, 2019). The decline in abundance of ants with elevation could explain the decrease in the disturbance of small seeds in forests (Sam, Koane and Novotny, 2015). However, it does not explain the increase in attacks on small seeds in gardens at higher elevations. I speculate that at higher elevations other insects, or perhaps even small birds, may have started to attack small seeds, because food resources are generally scarcer at higher elevations of and competition by ants is reduced (Sam *et al.*, 2019). The disturbance on small seeds also increased with higher crop richness, as I hypothesized, because ants may be more abundant in more diverse food gardens (Armbrecht and Perfecto, 2003). Although I can speculate about the species causing the predation on artificial caterpillars and seeds along this elevational gradient, further studies would be required to ascertain the suggested patterns.

3.4.3 Foliar herbivory

Foliar herbivory on the three wild harvested plants measured here was lower than average values reported for wet tropical regions (Coley and Barone, 1996). However, my results correspond to findings by Sam *et al.* (2020) who report an average level of foliar herbivory on *Ficus* species along the Mount Wilhelm gradient of 2.4%. The amount of foliar herbivory varied among tree species, which shows that it is species specific, and may explain why my results differ from Coley and Barone (1996). The level of foliar herbivory in gardens was also low compared to estimates ranging from small sized coffee farms in Jamaica (Johnson *et al.*, 2009) to global estimates of herbivory in large agricultural fields (Oerke, 2006). I expected foliar herbivory to be higher in gardens compared to forests, but I found the opposite. Foliar herbivory in gardens may be low because at the start of the gardening season new gardens are burned which kills insects. Food gardens in PNG are normally used for two to three years, and rapid rotation of fields prevents the build-up of herbivore populations (Bianchi, Booij and Tscharntke, 2006). Also, a large variety of crops are planted within each garden. More diverse fields have been shown to limit herbivory in other agricultural systems (Poveda, Gomez and Martinez, 2008).

Along the elevational gradient I found that in the forests foliar herbivory increased up to 700 m and then decreased toward higher elevations, similar to Sam *et al.*'s (2020) results from *Ficus* species along the same gradient. This hump-shaped pattern may be driven by the abundance of herbivorous insects, which peak at mid-elevations as a result of favourable climatic conditions (Sam *et al.*, 2020) and high insect predation at low elevations (Sam, Koane and Novotny, 2015).

3.4.4 *Ecosystem services and disservices in tropical agriculture in Papua New Guinea*

My research shows that current levels of pest-related ecosystem services are relatively high compared to global estimates, whereas levels of pest-related disservices are relatively low. Levels of both ecosystem services and disservices varied according to environmental factors including elevation and habitat. Current agricultural practices, including making gardens close to forests, burning gardens at the start of the season and planting a high variety of crops, are likely to contribute to favourable levels of biotic pest control and low pest levels, and thus ultimately to increased yields. I also show that some species, such as ants, are likely to contribute to both services (insect predation) and disservices (seed disturbance), which is important to keep in mind when promoting strategies to increase biotic pest control. However, many crops in PNG (e.g. sweet potato) are propagated vegetatively by planting suckers, tubers, cuttings or shoots so farmers do not always rely on seeds germinating (Bourke and Harwood, 2009). Herbivory, on the other hand, is a higher concern. Even though current levels of foliar herbivory are low, herbivory affecting only 2% of total leaf area has been shown to cause reductions in plant growth (Zvereva, Zverev and Kozlov, 2012). So even these low levels of herbivory are likely to negatively affect crop yields and tree growth. To further reduce the impact of herbivory, farmers could consider planting species that are less affected by pests or, if available, use pest-free materials (Johnson and Gurr, 2016).

3.4.5 *Looking forward*

The current patterns of ecosystem services and disservices in PNG are at risk due to social and ecological changes. Due to increasing land shortage, fallow times are being reduced, garden-use prolonged and forests cut (Shearman *et al.*, 2009; Fujinuma *et al.*, 2018), all of which are likely to promote the build-up of herbivorous insects in gardens. Also, the predicted increased temperatures and humidity in PNG as a result of climate change will favour pest species and may make crops more vulnerable to damage (Rosenzweig *et al.*, 2001; Sam *et al.*, 2020). Therefore, the level of herbivory in gardens is likely to increase in the future. Increases in herbivory may affect crops at higher elevations more than lower elevations because pest-related ecosystem services are currently relatively low at high elevations. Therefore, swidden farmers at higher elevations may be particularly detrimentally affected as the climate changes. However, increased temperatures may also cause an increase in ant and bird activity (Sam, Koane and Novotny, 2015; Orivel *et al.*, 2018), potentially mediating increased activity of herbivorous arthropods (Tiede *et al.*, 2017). These predictions are made with caution because inter-relationships among changes in temperature and species interactions are difficult to predict (Montoya and Raffaelli, 2010). Forests contain important wild harvested plants, and the current patterns of ecosystem services and disservices in forests may also change. However, forests may be less affected by climate change compared to gardens because the higher canopy cover in forests may buffer changes in abiotic conditions (Pohlman, Turton and Goosem, 2009).

In the face of social-ecological changes, it will be even more crucial for swidden farmers in PNG and across the tropics to continue using strategies to optimise ecosystem services and minimise ecosystem disservices in their gardens, so they can maintain yields sustainably. My observational approach provides valuable information about the level of ecosystem services and disservices across the landscape, and can contribute to our understanding about drivers of ecosystem services and disservices and their impact on crop yields. Wild harvested plants may also become an even more important food resource, and future scenarios for smallholder food security should consider the use of and impact on both crops and wild plants together, as I have done here.

I recommend that pest-related ecosystem services and disservices are closely monitored to provide a reliable evidence base and early warning system that smallholders could use to identify how and when to adapt their practices to maintain favourable levels of these ecosystem services and disservices.

3.5 Conclusion

Here I quantified pest-related ecosystem services and disservices in a swidden farming system in PNG, and identified how they were affected by environmental factors. I found that the current agricultural system has favourable levels of pest predation, seed disturbance and foliar herbivory. Elevation had the greatest influence on pest-related ecosystem services and disservices, which generally decreased with increasing elevation. This research is timely because current levels of biotic pest control are increasingly at risk from social and ecological changes. Close monitoring of pest-related ecosystem services and disservices in smallholder agricultural systems will be crucial to continue building up an evidence base that farmers can use to maintain favourable levels of pest-related ecosystem services and disservices, and consequently maintain or even increase their crop yields.

- Chapter 4 -

Using locally available fertilisers to enhance the yields of swidden farmers in Papua New Guinea

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Mama Hagar teaches me how to plant yams in Baitabag, Papua New Guinea.

'Don't judge each day by the harvest you reap but by the seeds that you plant.'

- Robert Louis Stevenson

Abstract

1. Swidden agriculture (a type of small-scale agriculture) is crucial to the livelihood and food security of millions of people in tropical regions. Social-ecological changes, including population growth and anti-swidden policies, are putting pressure on the existing swidden system to increase agricultural productivity in a sustainable way. Enhancing soil fertility is a promising option for increasing crop yields and extending lifetimes of agricultural fields, thereby reducing the demand to clear new land. However, there is limited information on how swidden farmers can best maintain soil fertility.
2. My aim was to investigate whether using locally available fertilisers can increase soil quality, crop yields and lifetimes of swidden fields.
3. I established experimental gardens on the land of swidden farmers in the Lowlands of Papua New Guinea, where the majority of the population depends on swidden agriculture. Gardens were set up on two types of sites; five were established on new sites that had just been prepared for gardening by cutting and burning vegetation after a fallow period, whereas another five were prepared on garden sites that were just being fallowed. I applied three treatments: (1) compost consisting of decaying banana peels, (2) chicken manure, and (3) NPK fertiliser to different plots within each garden; and tracked soil quality and yields of sweet potato over 12 months (three post-intervention cropping periods). I also conducted in-depth interviews with local farmers to understand their perspective on soil management.
4. Few farmers typically used compost, chicken manure or NPK fertiliser. Many were keen to try these fertilisers, provided they had more information. The performance of treatments depended on the type of garden with chicken manure increasing tuber yields in fallowed gardens but not new gardens, and banana peel compost also increasing tuber yields in fallowed gardens although not significantly. NPK fertiliser was the best option because it was the only fertiliser that increased yields in both new and fallowed gardens,

produced tubers of similar quality and taste to control plots and was financially profitable. Treatments affected yield through increasing available nitrogen and reducing soil moisture. I also found that farmers fallow their gardens despite adequate sweet potato yields, so whether using fertilisers can enhance the lifetime of fields will depend on additional factors such as labour input needed.

5. This work shows how swidden agriculture can potentially be adapted so that it continues to be a sustainable way of farming and living.

4.1 Introduction

Large areas of tropical forest landscapes are occupied by swidden cultivation (Padoch and Pinedo-Vasquez, 2010). Within this type of agriculture, forest is converted to agricultural land by cutting and subsequently burning trees, the ashes being used to enhance soil fertility (Gay-des-Combes *et al.*, 2017). After a short duration of cultivation (usually one to two years), farmers move to farm a new area while the old area is fallowed (Padoch, 2018). The main reasons for leaving a field to fallow include severe weed infestation, high pressures of pests and pathogens, and soil nutrient exhaustion (Sirén, 2007). Parts of the fallow are often planted with useful tree crops either for subsistence or cash income (Mertz, Padoch, *et al.*, 2009). After a comparatively long fallow period (which usually lasts more than two years, depending on the region) swidden farmers return to the same area to clear and crop it again (Padoch, 2018). Swidden agriculture plays a crucial role in sustaining the livelihoods of many people living in tropical forests, with estimates ranging from 40 million to one billion people (Mertz, Leisz, *et al.*, 2009).

Going forward swidden farming needs to adapt to demographic and political pressures. Swidden systems will have to continue to adapt to larger populations (van Vliet *et al.*, 2012). As populations have increased, swidden farmers have often decreased the length of the fallow period (Sirén, 2007; Dressler *et al.*, 2016). Reduced fallow periods have been shown to reduce soil quality and productivity in swidden fields (Bruun *et al.*, 2017; Fujinuma *et al.*, 2018), although it is unlikely that shorter fallow periods will eventually lead to a collapse of the swidden system (Mertz *et al.*, 2008). There has also been a rise in anti-swidden policies, including prohibitions for conservation purposes (Fox *et al.*, 2009). Swidden agriculture has often been criticised for driving deforestation and forest degradation (Heinimann *et al.*, 2017). However, there is growing evidence that when swidden cultivation is discontinued it is often replaced by intensified land uses such as sedentary agriculture or commercially driven large scale plantations with higher environmental impacts (van Vliet *et al.*, 2012). Swidden cultivation itself can actually harbour high levels of biodiversity (Padoch and Pinedo-Vasquez, 2010). So, there is a place for swidden cultivation in conservation landscapes, but swidden farmers may have to further limit the impact on their surroundings. Improving the productivity and sustainability of the existing swidden system is thus necessary so that it can continue to be a viable livelihood.

Enhancing soil fertility is a promising option for increasing crop yields and extending the lifetime of a field, thereby reducing the demand to clear new land (Gay-des-Combes *et al.*, 2017; Fujinuma *et al.*, 2018). At the moment there is limited information on the impact of swidden agriculture on essential nutrients and how soil fertility can best be maintained within the swidden system (Mukul and Herbohn, 2016). Currently, burning of fields is widely practised because, besides clearing the land of remaining vegetation, it improves the physiochemical properties of the soils and thus favours crop growth (Kukla *et al.*, 2019). The effects on the soil are, however, short-lived. During the burning process considerable amounts of nitrogen (N) and carbon (C) are lost to the atmosphere (Demeyer, Voundi Nkana and Verloo, 2001). The nutrients which are retained in ash patches are considered at risk of being lost through both leaching and erosion, with potassium (K) being particularly vulnerable to leaching and phosphorus (P) to erosion of ashes (Menzies and Gillman, 2003). Hence, there are limits to the extent ash fertilisation can sustain crop yields, especially in the long term, and there is merit in exploring additional soil fertilisation methods (Gay-des-Combes *et al.*, 2017).

Research to improve the productivity of the swidden system is needed across the tropics (Mertz *et al.*, 2008). It is especially necessary in Papua New Guinea (PNG), because more than 75% of the population depends almost entirely on swidden agriculture (Conservation and Environment Protection Authority, 2019). The population in PNG has grown from 2.3 million people in 1960 to 8.9 million people in 2020, and the annual population growth is currently 2% (The World Bank Group, 2020a). Increasing food production of swidden farmers in PNG is thus essential, even if existing yields are adequate for the current population. At the same time, PNG contains the third largest area of tropical forest worldwide. The country is home to circa 7% of the world's biodiversity and at least 30% of species are thought to be endemic (Conservation and Environment Protection Authority, 2019; UNDP, 2021). There is thus limited land available for expansion by swidden farmers in PNG, other than mainly high conservation value areas. Swidden agriculture in PNG generally involves a family (5-10 people, including children) clearing and burning up to three small primary or secondary forest areas surrounding their village each year. The resulting fields are called 'food gardens' in which a combination of food crops, such as sweet potato and banana, is grown. Increasingly, cash crops, such as coffee and cacao, are planted alongside food crops, which are mostly sold on informal markets (Bourke and Harwood, 2009). In addition, people may prepare a couple of small plots closer to their house where they mainly grow vegetables (Sillitoe, 1999). After 1-5 rounds of crop planting, gardens are left to fallow for usually 5-15 years (Bourke and Harwood, 2009). So far most farmers in PNG have responded to the increased need for land to grow food and cash crops by reducing their fallow periods (Hoover, Leisz and Laituri, 2017; Fujinuma *et al.*, 2018). This has caused a reduction in soil fertility and decreased yields, which are both very likely to worsen in the future because further land-use intensification is anticipated (Fujinuma *et al.*, 2018). Therefore, investigating how soil quality can be enhanced in swidden fields in PNG so that crop yields and the lifetime of food gardens can be increased, could benefit both food security and biodiversity conservation.

Most data on the effect of soil fertility on yield in PNG come from research stations, with very few recordings from village gardens, especially in the Lowlands (< 600 m elevation; Hartemink & Bourke, 2000). Also, most research so far has focused on newly prepared gardens and not on fallowed ones, even though fallowed gardens will have to be reused soon in order to address the issues of land shortage. I define fallowed gardens as gardens which are less intensively managed. People may still return to a fallowed garden to harvest longer-lived crops or useful tree species, but no longer regularly clean and weed the area (Vira, Wildburger and Mansourian, 2015). Finally, so far studies in PNG have focused on the effect of inorganic fertiliser on crop yields (Hartemink and Bourke, 2000). However, it is useful to develop a wide range of soil fertility management tools as farmers may differ in their attitudes towards certain practices or be restricted in the type of fertiliser that they can acquire due to a lack of cash or access to markets (Bourke and Harwood, 2009; Fujinuma *et al.*, 2018). The use of plant materials and manure from livestock has been identified by PNG's National Agricultural Research Institute as promising fertilisers, and thus warrant further investigation (Askin, 2019).

My aim in this study was therefore to investigate whether using locally available fertilisers can enhance soil quality and increase crop yields in both new gardens and gardens that have been fallowed for one or two years. I addressed four questions. First, how do different types of locally accessible fertilisers (compost made up of decaying banana peels, chicken manure, and NPK fertiliser) influence soil quality in new and fallowed gardens? Second, do these fertilisers increase crop yields compared to control plots in new and fallowed gardens? Third, what are the relationships between treatment, soil quality and yield? Fourth, are local farmers interested in using these soil management techniques, and what are the barriers to taking-up these practices? Experimental gardens were set up on the land of swidden farmers in the Lowlands of PNG, in which I grew sweet potato. This crop was chosen because it is an important staple food in PNG (Bourke and Harwood, 2009). Compost in the form of decaying banana peels, chicken manure and NPK fertiliser were applied to different plots in the experimental gardens, and soil quality and crop yields tracked over three subsequent cropping periods spanning over 12 months. I also conducted in-depth interviews with local farmers to better understand their perspective on using compost, chicken manure and NPK fertiliser.

I hypothesised that decaying banana peel compost, chicken manure, and NPK fertiliser would increase soil nutrients, specifically the nitrogen, phosphorus and potassium content of soil. Nitrogen, phosphorus and potassium are important macronutrients for sweet potato (O'Sullivan, Asher and Blamey, 1997). Nitrogen and potassium are most likely to influence sweet potato yields. Nitrogen levels in PNG soil are often too low for sweet potato to yield well (Hartemink and Bourke, 2000). Sweet potato has a high requirement for potassium and especially soils which have seen several rounds of crop plantings already may be potassium deficient (O'Sullivan, Asher and Blamey, 1997). Phosphorus, on the other hand, is less likely to determine yields as sweet potato is an effective phosphorus scavenger (Sillitoe, 1996). Besides increasing soil nutrients, I expected decaying banana peel compost and chicken manure to increase soil moisture

(Amanullah, Sekar and Muthukrishnan, 2010; Gay-des-Combes *et al.*, 2017). This is because organic materials have been shown to improve soil physical properties, for example by reducing bulk density, which consequently increase the soil water content (Bassouny and Chen, 2015). NPK fertiliser, on the other hand, was not expected to directly affect soil moisture (Tadesse *et al.*, 2013; Bassouny and Chen, 2015). However, fertilisers can have indirect effects on soil moisture via plant growth; increased plant biomass stores more water and increases evapotranspiration, causing soil moisture to decrease (Bhatt and Hossain, 2019). A volumetric soil moisture level of 17-20% is ideal for sweet potato tuber development (Gajanayake *et al.*, 2013), so depending on the soil moisture conditions present, decreased or increased soil moisture levels may be beneficial. As a result of soil physical and chemical improvements, I predicted that adding composting banana peels, chicken manure or NPK fertiliser would increase the nutrient status of plants and tubers, sweet potato yields and crop quality.

4.2 Materials and Methods

4.2.1 Study site

Field sampling was conducted in Ohu (S 05°13.081', E 145°40.735', 150 m elevation), which is 12 km west of the town of Madang, on the North coast of PNG (Fig. 4.1). Ohu was selected because the village is representative of other landscapes in Madang province and Lowland PNG in general. The original mosaic of primary and secondary forest around the village has changed since the 1980s into a more intensely managed landscape with food gardens, young secondary forest on fallowed food gardens, family plantations and village settlements (Sam *et al.*, 2014). Some of the remaining fragments of primary forest are being preserved as a community-based protected area, supervised by village landowners, where hunting, logging and gardening are forbidden (Weiblen and Moe, 2016). However, population growth is putting pressure on these forest fragments. The average rainfall in the Madang area is 3558 mm, with a moderately dry season from July to

September. Mean air temperature is 26.5°C and varies little throughout the year (McAlpine, Keig and Falls, 1983). Soils in Ohu are a mixture of dystropepts and eutropepts inceptisols (Bryan and Shearman, 2008).

4.2.2 Local practices in Ohu

At the start of the experiment in August 2018, I conducted in-depth interviews with local farmers in Ohu in which I asked about past, current and future diets, crops planted in food gardens, past and current land use and agricultural techniques used in food gardens. I interviewed a total of 23 people and selected participants with the help of a village leader. I asked both younger (18-40 years) and older (> 40 years) people, and men and women to participate, as the use and distribution of resources in PNG can differ between these groups. Free prior-informed consent was given by all participants before the start of the interview. The average length of an interview was 60 minutes. The protocol was approved by the University of Oxford's Research Ethics Committee under permit number R58337/RE001.

4.2.3 Experimental gardens

4.2.3.1 Design

Ten experimental gardens were set up in Ohu on the land of local farmers in August 2018. Five gardens were set up on sites that had just been prepared for gardening by clearing and burning the area. Five other gardens were set up on sites that had been prepared in 2015 or 2016, used for food production by farmers afterwards and had just been fallowed (Fig. 4.1). Landowners were compensated for the use of their land. At the start of the experiment, all vegetation in and around the experimental gardens was removed, and deposited at least 50 meters away from the site.

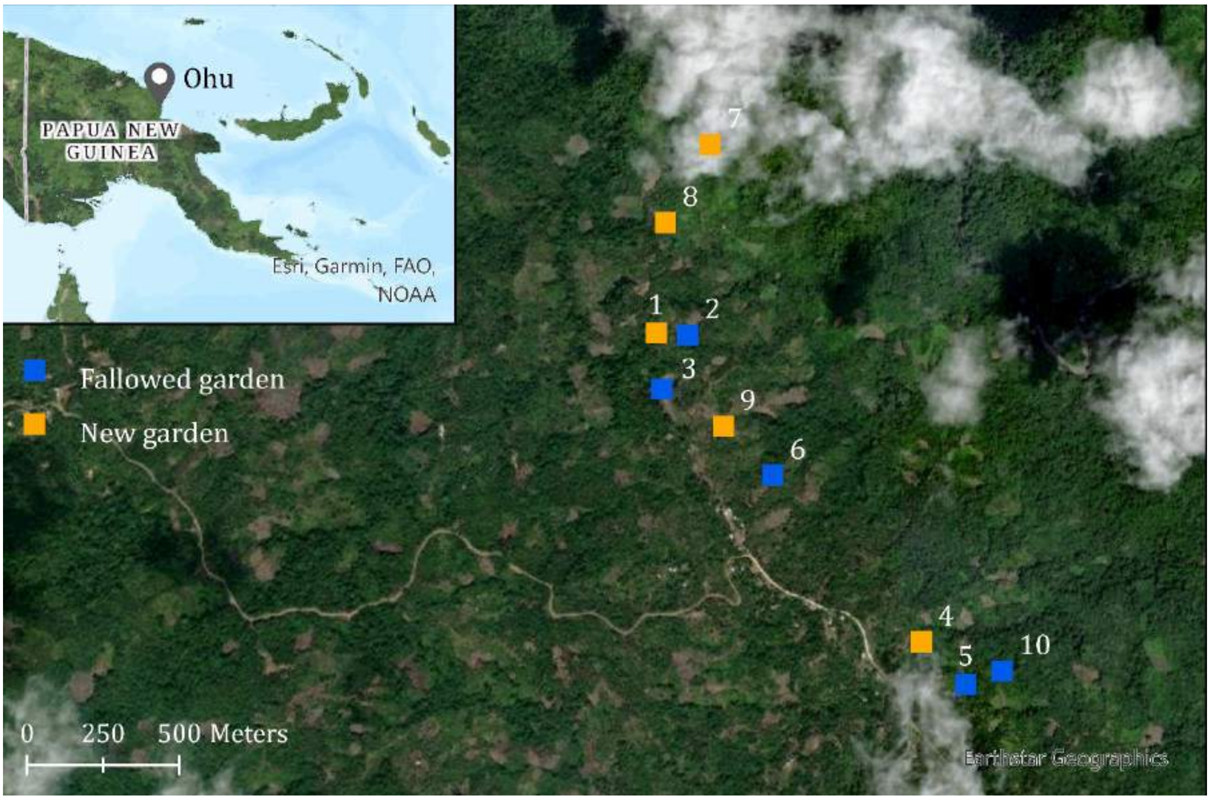

Figure 4.1 | Overview of the geographical locations of the experimental gardens in Ohu, PNG.

Within each experimental garden, four 3.5 x 3.5 m plots were randomly allocated to one of the following treatments; control, compost, manure and NPK fertiliser (Fig. 4.2A). Fertilisers were chosen as they contain either nitrogen or potassium or both in high amounts, and these nutrients are important determinants of sweet potato yields (Table 4.1). All fertilisers were sourced locally, and could potentially be used by farmers themselves. For compost, fresh banana peels were collected from the food waste of local farmers and left to decay for a maximum of two months (this treatment is from here on called compost only), fresh chicken manure was sourced from a local farmer, and NPK fertiliser (12% - 12% - 17%) was bought in a shop in Madang town. The fresh chicken manure was dried in the sun for 2-3 weeks before it was used to reduce ammonia emissions which can harm roots, and to kill unwanted weed seeds and pathogens present in the manure.

Recommendations for the application of potassium fertilisers to sweet potato generally lie between 80 to 200 kg K/ha and for nitrogen fertilisers between 30 and 90 kg N/ha (O'Sullivan, Asher and Blamey, 1997). Therefore, in the compost treatment I aimed to add 200 kg K/ha, and in the chicken manure and NPK fertiliser treatments 40 kg N/ha (Table 4.1). The nitrogen, phosphorus, potassium and water content in compost, chicken manure and NPK fertiliser were determined at the start of the experiment, and I calculated application rates based on the measured values (Appendix B, Table 1).

Table 4.1 | Estimated inputs of nitrogen, phosphorus and potassium in kg/ha for each treatment, based on the weight of material applied and estimated using the data in the Appendix B, Table 1.

Treatment	Input N (kg/ha)	Input P (kg/ha)	Input K (kg/ha)
Control	0	0	0
Compost	9.6	1.2	200
Chicken manure	40	17	119
NPK fertiliser	40	40	57

Within each plot 25 mounds of 0.7 x 0.7 x 0.4 m were made, following local practices (Fig. 4.2B). In the compost treatment, 358 grams of decayed banana peels was added to each mound 4-6 days before planting, and at the same time 68 grams of dried chicken manure was applied in the manure treatment. In the NPK fertiliser treatment, 16 grams of NPK fertiliser was administered to each mound at the time of planting, as this type of fertiliser does not need to be broken down before nutrients become available to plants, which is different from compost and chicken manure.

At the start of each planting in August 2018, December 2018 and April 2019, three sweet potato vines were planted in each mound, again following local practices. I used a local sweet potato *Ipomoea batatas* (L.) Lam variety called 'wan mun kaukau'. The species has a growth cycle of approximately 90 days in Ohu and thus harvests were completed in November 2018, March 2019 and July 2019. Plots were weeded by farmers throughout the experiment, following local practices.

Measurements were taken only on the nine mounds inside a plot. The 16 mounds at the edge of each plot were not measured as they could have been influenced by spill over effects from neighbouring plots or food gardens.

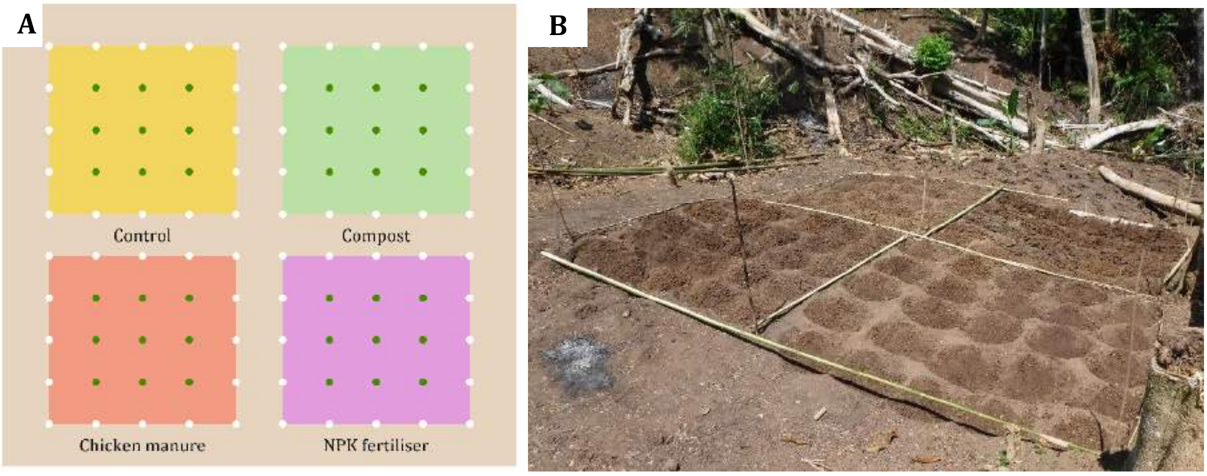

Figure 4.2 | Schematic overview of an experimental garden. Each dot represents a sweet potato mound with white dots indicating mounds in the guard rows which were ignored, and green dots indicating mounds inside a plot from which measurements were taken (A). Photograph of the set up in the field (B).

4.2.3.2 Soil nutrient content

Soil samples (circa 500 g) were collected at 10 cm depth within each plot at the start of the experiment and before each harvest. One sample was collected from the base of the mound and another sample was collected from in between mounds. Five sub-samples (circa 100 g) were taken, separated by a minimum distance of 1 m, pooled together to reduce heterogeneity and oven dried at 105°C for approximately 8 hours. Dried soil samples were shipped, under permit, to Charles University in the Czech Republic for laboratory analyses.

Soil samples were analysed for their conductivity, pH, total nitrogen, phosphorus, potassium and carbon, and available nitrogen, phosphorus and potassium. Conductivity and pH were determined in a 1:5 soil:water suspension using a glass and potentiometric electrode. Samples of dry soil were milled and homogenized by a ball mill (Retsch MM 400 Mixer Mill). Then samples were dried at 40°C for 12 hours. For measuring total nitrogen and carbon content, samples were weighed (Mettler-Toledo MX5) and put into capsules. Total nitrogen and carbon content were determined using an elemental analyser (Flash 2000 Thermo Fisher Scientific). For measuring total phosphorus and potassium content, samples were mineralised in nitric acid for 30 minutes and in perchloric acid for 3 hours. Total phosphorus was measured by colorimetric analysis using a spectrophotometer at 889 nm (UV VIS Genesys 10, Thermo Fisher Scientific) following Murphy and Riley (1962). Total potassium (383 nm) was quantified by flame atomic absorption spectrophotometry (PerkinElmer 306). Inorganic nitrogen (NO_3^-) was measured in a 1:5 soil:water suspension and determined using a spectrophotometer at 210 nm (Genesys™ 10S UV-Vis, Thermo Fisher Scientific). Available forms of phosphorus (PO_4^{3-}) were quantified after extraction in a Mehlich III solution with a 1:10 soil:Mehlich ratio using ascorbic acid and ammonium molybdate as a reducing agent following Murphy and Riley (1962), and then using a spectrophotometer at 889 nm (Genesys™ 10S UV-Vis, Thermo Fisher Scientific). Available potassium (383 nm) was quantified by flame atomic absorption spectrophotometry (PerkinElmer 306).

4.2.3.3 Soil moisture

Volumetric soil moisture was measured within each plot at the start of the experiment, and again before each harvest. Measurements were taken in between mounds and at the base of mounds at 10 cm depth with a SM150 Soil Moisture Sensor (Delta-T) using the pre-set mode for mineral soil which is accurate to ± 3%. Five measurements separated by a minimum distance of 1 m were taken within each plot.

4.2.3.4 Plant- and tuber nutrient content

The first fully developed leaf from the apex was collected from four different vines within each plot at the time of harvest. Also, four tubers were collected from every treatment, and a 1 cm slice was cut from the middle of the tuber. The leaves and slices were dried using silica gel (Sigma-Aldrich), packed into plastic bags and transported, under permit, to Charles University for further laboratory analysis.

Leaves and tubers were analysed for their total nitrogen, phosphorus, potassium and carbon content. Samples of dry biomass were milled and homogenised using a ball mill (Retsch MM 400 Mixer Mill). In case samples had taken up water from the air during milling, they were dried again at 40°C for 12 hours. Samples were then weighed (Mettler-Toledo MX5) and put into capsules. Total nitrogen and carbon content were determined using an Elemental Analyzer (Flash 2000 Thermo Fisher Scientific). For measuring total phosphorus and potassium content samples were mineralised in nitric acid for 30 minutes followed by perchloric acid for 3 hours. Total phosphorus was measured by colorimetric analysis using a spectrophotometer at 889 nm (UV VIS Genesys 10S, Thermo Fisher Scientific), following Murphy and Riley (1962). Total potassium (383 nm) was quantified by flame atomic absorption spectrophotometry (PerkinElmer 306).

4.2.3.5 Yield of leaves, vines and tubers

Approximately 90 days after planting, mounds were harvested, and sweet potato tubers, leaves and vines were collected. First, leaves and vines were collected from each mound, they were separated, and then weighed individually on a digital scale (Heston Blumenthal). Next, mounds were destroyed and all the tubers were collected. Tubers were washed and their skin dried before being weighed. The yield of leaves, vines and tubers was calculated per mound.

4.2.3.6 Quality of tubers

Each tuber was assessed visually by local farmers and ranked as either 'unfit for human consumption' if the tuber would have to be thrown away or could only be fed to livestock or pets, or 'fit for human consumption' if the tuber could be consumed by humans or sold on local markets. Factors that determined the ranking of a tuber included tuber size and the extent to which it had been attacked by insects, earthworms, rats or pathogens.

4.2.3.7 Taste test

A blind tasting experiment was performed at the end of each harvest. During harvests I collected one marketable tuber from each plot from every garden. The tubers were put in different pots based on the treatment they had been grown in. One cook, who was unaware of which pot related to which treatment, prepared the tubers for consumption by peeling them, cutting them in equal-sized slices, and boiling them in water without adding any flavours, spices or other food.

Participants, also blind to which pot represented which treatment, were subsequently asked to eat a slice from each pot, describe the taste of each slice and why or why not they liked it, and rank the slices from the different pots among each other. A total of 51 participants took part in the tasting experiment.

4.2.4 Statistical analyses

The goal of the analyses was to: (1) examine the effect of treatment (control, compost, chicken manure or NPK fertiliser) on soil quality and yield in both new and fallowed gardens, (2) investigate whether treatments had different effects in new versus fallowed gardens, and (3) understand the causal relationships between treatment, soil quality and yield.

To examine the effect of treatment in new and fallowed gardens on soil chemical properties, soil moisture and the yield of sweet potato leaves, vines and tubers, I split the data set into two based on whether it was a new or fallowed garden. Analyses were run on the two data sets independently with treatment included as a fixed effect. To correct for temporal pseudo-replication, harvest number was included as a fixed effect. Plot number nested within garden number was included as a random intercept effect where data were collected at the mound level (for soil moisture and yield data), and garden number only was included where data were collected at the plot level (for soil chemical properties data). In 5.6% of the mounds a combination of two different varieties of sweet potato, as judged by the colour and shape of the leaves and tubers, was accidently planted, although both varieties have a growth cycle of approximately 90 days. In the models for yield I included whether a mound contained only the main variety of sweet potato or a combination of the two varieties as a fixed factor to control for this. For a full overview of the specification of the models, see Appendix B, Table 2.

To investigate how the effect of treatment differed between new and fallowed gardens, I ran the analyses on the full data set including both new and fallowed gardens. I included an interaction effect between treatment and garden type as fixed effects, and I corrected for pseudo-replication in time and space and the presence of a different variety similarly to described above. I fitted this model to data on soil, plant and tuber chemical properties, the yield of sweet potato leaves, vines and tubers, and tuber quality. For the taste test analysis, I included treatment as a fixed effect, as well as harvest number to correct for temporal pseudo-replication. For a full overview of the specification of the models, see Appendix B, Table 3.

To examine the links between soil quality and yield I built an a priori conceptual model of hypothesized causal relationships within a path model (Appendix B, Table 4). I then used structural equation modelling (SEM) to directly test the supposed causal structure. SEM was designed for continuous variables that are normally distributed and it is advised to convert factors into dummy variables. Thus I included treatment and the type of garden as dummy variables with control and new gardens as the respective reference levels. In this model I again corrected for temporal and spatial pseudo-replication by including harvest number as a fixed effect and garden number as a random intercept effect. For a full overview of the specification of the SEM model, see Appendix B, Table 5. To check whether the hypothesized relationships were consistent with the data I calculated Fisher's C and its associated p-value.

All statistical analyses were done in R version 4.0 (R Core Team, 2020). For soil, plant and tuber chemical data the data were normally distributed and I fitted a linear mixed model using the 'lmer' function in the lme4 package (Bates *et al.*, 2019). Soil moisture measurements were recorded in percentages, and thus I used a beta distribution to fit the model. For the data set on the yield of sweet potato leaves, vines and tubers I opted for a gamma distribution because the yield data were bounded at zero and positively skewed. Counts of tubers per mound were analysed using a Poisson distribution. For beta, gamma and Poisson distributed models I used the 'gamlss' function in the gamlss package (Stasinopoulos *et al.*, 2020). Tuber quality followed a binary distribution and I conducted a logistic regression using the 'glmer' function in the lme4 package (Bates *et al.*, 2019). Results from the taste test were analysed using the 'clm' function from the ordinal package (Christensen, 2019). Where appropriate collinearity between independent variables was tested using the variable inflation factor. For the structural equation model I used the 'psem' function in the piecewiseSEM package (Lefcheck, Byrnes and Grace, 2019). I only included a few unrelated independent variables in my models, so I report values from the full models. Data from the experimental gardens is deposited in the Mendeley Data repository: http://dx.doi.org/10.17632/vybb4wcbb7.1. Means are reported with standard errors (s.e.).

4.3 Results

4.3.1 Local practices in Ohu

All 23 interviewees indicated that they relied on their gardens for their daily food. People complemented their garden food with foraging in the forests and buying food (mainly rice) from stores. Families maintained an average of 1.5 ± 0.13 food gardens (range zero to two) and 1.3 ± 0.29 smaller vegetable gardens (range zero to six). A variety of crops were intercropped in food gardens with banana, Chinese taro, taro and sweet potato being planted most often.

Interviewees pointed out that within their lifetime (the average age of interviewees was 42 years) fallow times have decreased from an average of 8.5 ± 1.3 years to 3.6 ± 0.25 years, and that the lifespan of a garden has increased from 2.0 ± 0.20 years to 2.3 ± 0.20 years. When discussing this and without being prompted, the majority of people indicated that they had seen yields declining in their lifetime.

At the time of the interview, none of the interviewees used NPK fertiliser. Fifty-two percent of interviewees sometimes applied compost in the form of food waste and 35% animal manure, but only in their smaller vegetable gardens. Only 4% of respondents used compost or animal manure in their food gardens. The most often cited reason for not using compost, animal manure or NPK fertilisers in their food gardens was that people were not always sure how to use these fertilisers. All interviewees were keen to try out animal manure, 87% compost and 83% NPK fertiliser, provided they had more information on how to use these fertilisers.

4.3.2 Experimental gardens

Before the start of the experiment, the amount of soil nutrients and level of soil moisture did not differ between control and treatment plots. Only the level of total potassium was significantly higher in NPK fertiliser plots in fallowed gardens compared to control plots. However, this is unlikely to have influenced my results because the level of available potassium has a more direct influence on plant growth compared to total potassium, and available potassium did not differ between NPK fertiliser and control plots. Also, the levels of available and total potassium were high in all plots and above the threshold for sweet potato to grow well (Nicholaides III *et al.*, 1985). New gardens contained a higher amount of available nitrogen, available and total phosphorus and available and total potassium compared to fallowed gardens, whereas fallowed gardens had higher levels of total nitrogen and soil moisture (Appendix B, Table 6).

4.3.2.1 Soil nutrient content

The amount of soil nutrients was significantly higher in mounds than between mounds (Appendix B, Table 7). Since sweet potato plants were planted in mounds and since their roots spread around 15 cm deep in the soil, only results based on measurements taken from mounds are reported below.

The application of treatments significantly affected the soil nutrient status compared to the control condition. Using compost significantly increased the amount of available potassium in the soil (Fig. 4.3E). Applying chicken manure, on the other hand, did not affect soil potassium levels, but increased the amount of available and total nitrogen, and available and total phosphorus in new gardens (Fig. 4.3A-F). In fallowed gardens, chicken manure had less of an effect (Table 4.2), and only increased the level of soil available phosphorus (Fig. 4.3C). NPK fertiliser, similar to chicken manure, increased the amount of available and total phosphorus in new gardens (Fig. 4.3C-D). Also NPK fertiliser had less of an effect in fallowed gardens (Table 4.2), and only increased the amount of total phosphorus (Fig. 4.3D). Contrary to chicken manure, NPK fertiliser did not affect soil available or total nitrogen levels in either new or fallowed gardens (Fig. 4.3A-B). Soils in fallowed gardens contained on average less available potassium than in new gardens (Table 4.2).

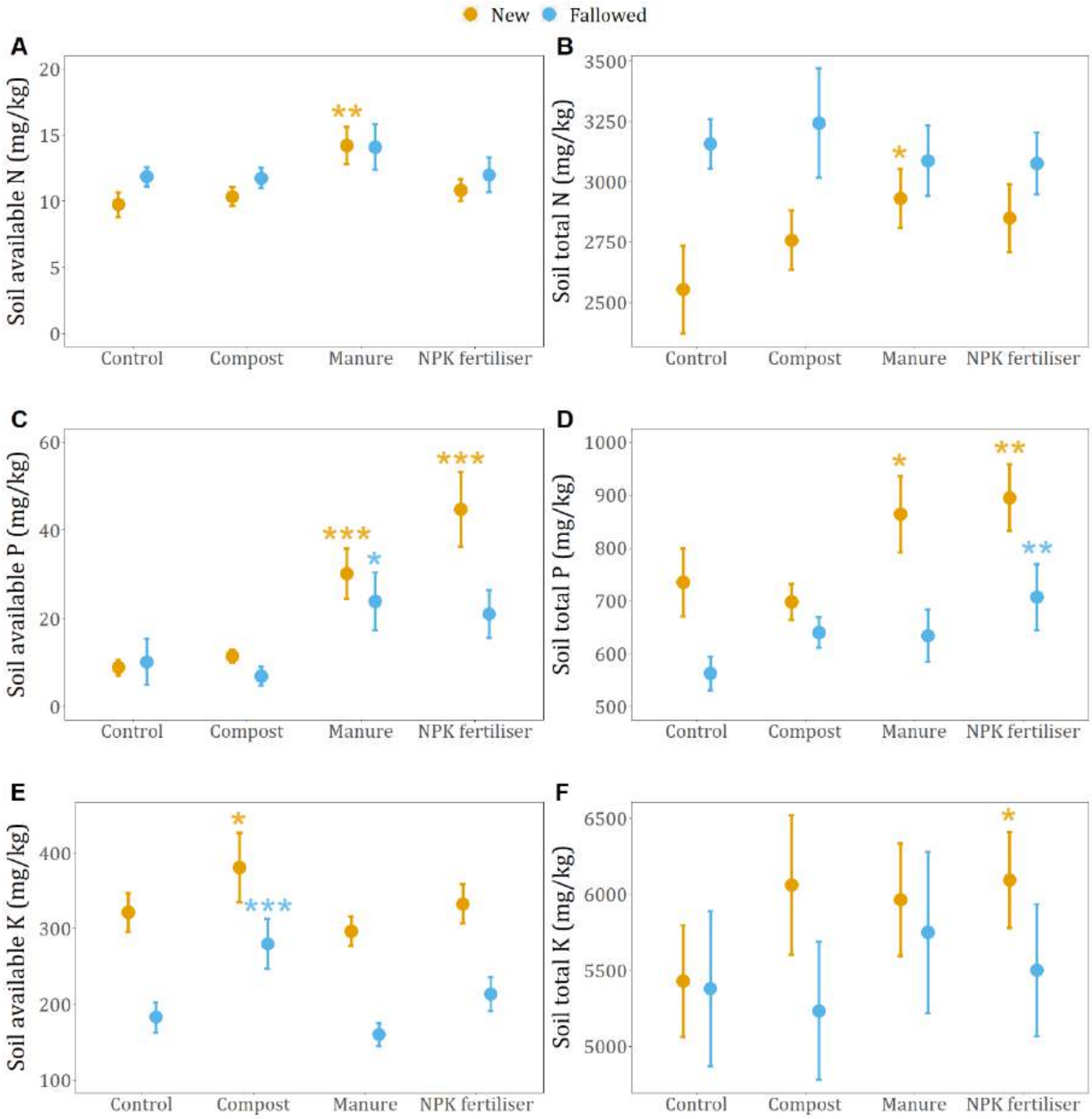

Figure 4.3 | Available nitrogen (A), total nitrogen (B), available phosphorus (C), total phosphorus (D), available potassium (E) and total potassium (F) in mg/kg for different treatments. Orange indicates new gardens and blue fallowed gardens. Mean ± s.e. are shown. * = p < 0.05, ** = p < 0.01, and *** = p < 0.001. For full results, see Appendix B, Table 8.

4.3.2.2 Soil moisture

Soil moisture was significantly lower in plots treated with NPK fertiliser compared to control plots in both new and fallowed gardens (Fig. 4.4). Compost only lowered the level of soil moisture in fallowed gardens, whereas chicken manure only lowered soil moisture in new gardens (Fig. 4.4). Fallowed gardens, overall, had a significantly lower percentage soil moisture compared to new gardens (Table 4.2).

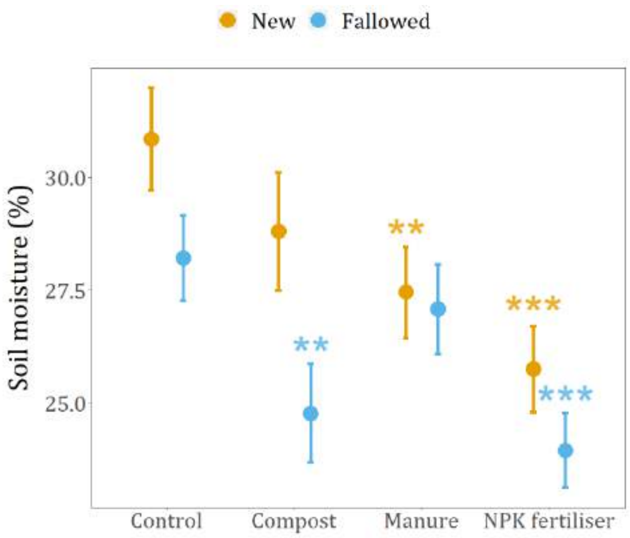

Figure 4.4 | Percentage of volumetric soil moisture for different treatments. Orange indicates new gardens and blue fallowed gardens. Mean ± s.e. are shown. * = p < 0.05, ** = p < 0.01, and *** = p < 0.001. For full results, see Appendix B, Table 8.

Table 4.2 | Summary of the model results for soil nutrients and soil moisture. ns = non-significant, +/- = $p < 0.05$, ++/-- = $p < 0.01$, +++/--- = $p < 0.001$, with + indicating a positive effect and - a negative effect. Reference levels are given in grey shading for each variable. For full results, see Appendix B, Table 9.

		Soil available N	**Soil total N**	**Soil available P**	**Soil total P**	**Soil available K**	**Soil total K**	**Soil moisture**
Treatment	Control							
	Compost	ns	ns	ns	ns	+	ns	ns
	Manure	++	+	+++	++	ns	ns	--
	NPK fertiliser	ns	ns	+++	+++	ns	ns	---
Garden type	New							
	Fallowed	ns	ns	ns	ns	-	ns	-
Harvest	Harvest 1							
	Harvest 2	++	--	+	ns	+	ns	+++
	Harvest 3	ns	ns	+	ns	ns	ns	---
Treatment * Garden type	Control : New							
	Compost : Fallowed	ns	ns	ns	ns	ns	ns	ns
	Manure : Fallowed	ns	-	ns	ns	ns	ns	ns
	NPK fertiliser : Fallowed	ns	ns	--	ns	ns	ns	ns

4.3.2.3 Plant and tuber nutrient content

The application of treatments did not significantly affect the amount of nutrients in plants or tubers. Plants in fallowed gardens contained a significantly lower amount of total nitrogen compared to new gardens (Appendix B, Table 10 and 11).

4.3.2.4 Yield of leaves, vines and tubers

In control plots, the yield of leaves, vines and tubers did not differ significantly between new and fallowed gardens (Table 4.3). However, the application of treatments significantly affected the yield of leaves, vines and tubers, and the effects differed for new versus fallowed gardens (Fig. 4.5A-D).

The compost treatment significantly decreased leaf and vine yields compared to the control treatment, but more so in new gardens compared to fallowed gardens (Table 4.3). Contrary to this, chicken manure and NPK fertiliser increased leaf and vine yields in new gardens. In fallowed gardens, chicken manure and NPK fertiliser only increased vine yields, but not leaf yields (Fig. 4.5A-B).

In new gardens that were treated with compost, tuber yields declined, similar to the leaf and vine yields. In fallowed gardens, however, tuber yields increased when treated with compost, although not significantly (Table 4.3). Applying chicken manure significantly increased tuber yields in fallowed gardens, but had no effect in new gardens. NPK fertiliser was the only fertiliser that increased tuber yields in both new and fallowed gardens, and had a greater effect in fallowed gardens compared to chicken manure (Fig. 4.5C).

The increase in yield was due to an increase in tuber number, rather than an increase in the mean average weight of a tuber. In control plots, an average of 4.8 tubers per mound was harvested. In fallowed gardens, applying compost increased the average number of tubers per mound by 0.85 tubers, while using chicken manure led to 1.4 additional tubers on average. NPK fertiliser increased the average number of tubers per mound by 2.5 tubers in fallowed gardens and 1.4 tubers in new gardens (Fig. 4.5D). None of the treatments increased the average weight per tuber. Compost even decreased the average weight per tuber, by 8.9 grams, in new gardens (Appendix B, Table 12).

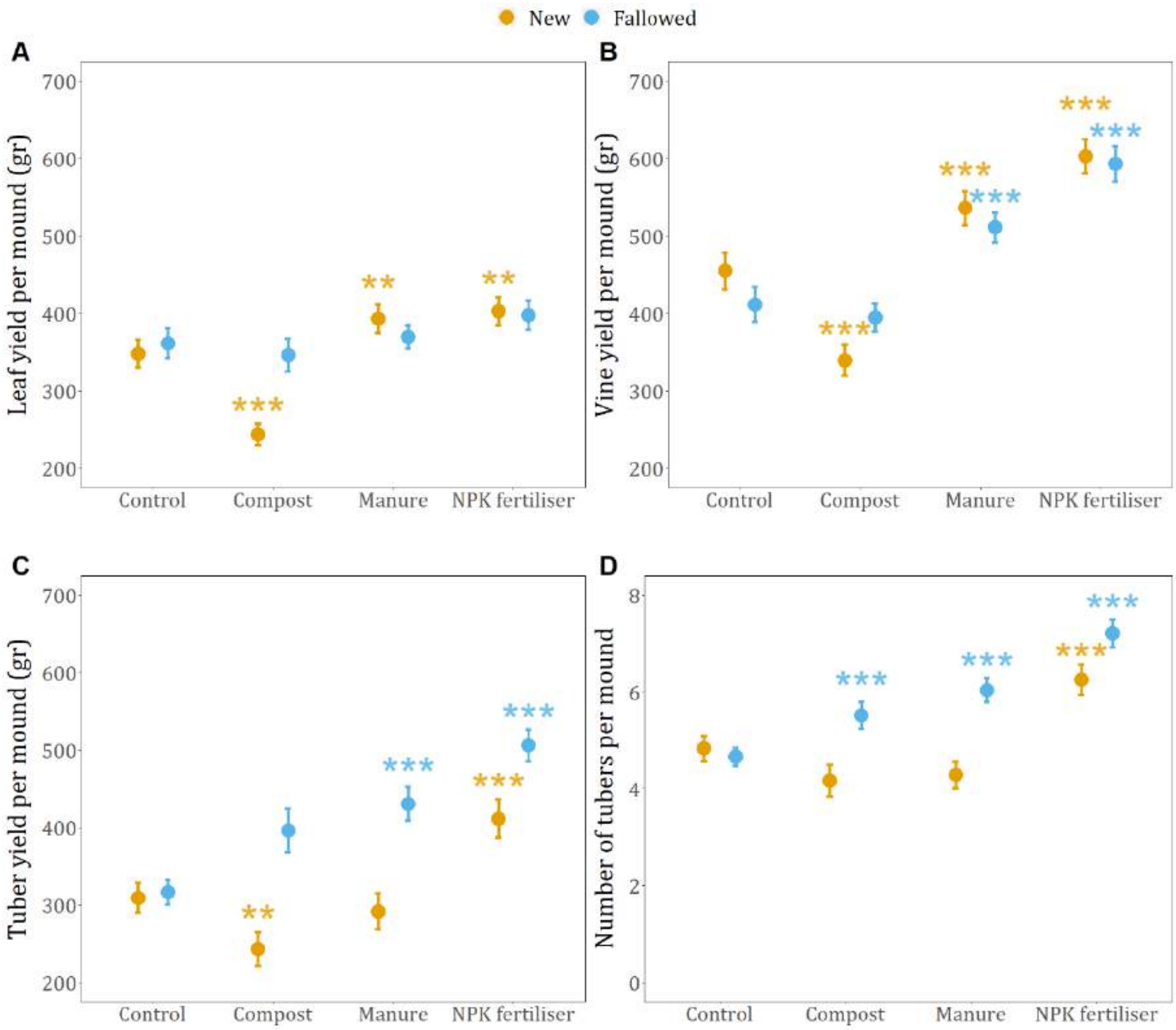

Figure 4.5 | Yield of leaves (A), vines (B) and tubers (C) in grams per mound, and number of tubers per mound (D) for the different treatments. Orange indicates new gardens and blue fallowed gardens. Mean ± s.e. are shown. * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$. For full results, see Appendix B, Table 12.

4.3.2.5 Quality of tubers

In the control condition, 62% of sweet potato tubers were classified as being fit for human consumption. Treatment with compost lowered the probability of sweet potato tubers being acceptable for human consumption by 39%. The application of chicken manure and NPK fertiliser did not significantly affect tuber quality. Tuber quality also did not differ between new and fallowed gardens (Table 4.3).

Table 4.3 | Summary of the model results for leaf yield, vine yield, tuber yield and tuber quality of tubers. ns = non-significant, +/- = $p < 0.05$, ++/-- = $p < 0.01$, +++/--- = $p < 0.001$, with + indicating a positive effect and - a negative effect. Reference levels are given in grey shading for each variable. For full results, see Appendix B, Table 13.

		Leaf yield	**Vine yield**	**Tuber yield**	**Weight per tuber**	**No. of tubers**	**Tuber quality**
Treatment	Control						
	Compost	---	---	--	--	ns	-
	Manure	++	+++	ns	ns	ns	ns
	NPK fertiliser	++	+++	+++	ns	+++	ns
Garden type	New						
	Fallowed	ns	ns	ns	+	ns	ns
Tuber type	Red						
	Mix	+	ns	ns	ns	-	-
Harvest	Harvest 1						
	Harvest 2	ns	--	ns	+++	---	+++
	Harvest 3	---	---	---	+++	---	-
Treatment *	Control : New						
Garden type	Compost : Fallowed	+	+	++	ns	+	ns
	Manure : Fallowed	-	ns	+	ns	+++	ns
	NPK fertiliser : Fallowed	ns	ns	ns	ns	ns	ns

4.3.2.6 Taste test

Tubers grown in compost and NPK fertiliser plots were ranked similarly compared to tubers grown in control plots, but tubers from chicken manure plots were ranked significantly lower (Fig. 4.6 and Appendix B, Table 14). Participants remarked that these tubers tasted less sweet and contained roots on their skin, which was why they did not prefer these tubers.

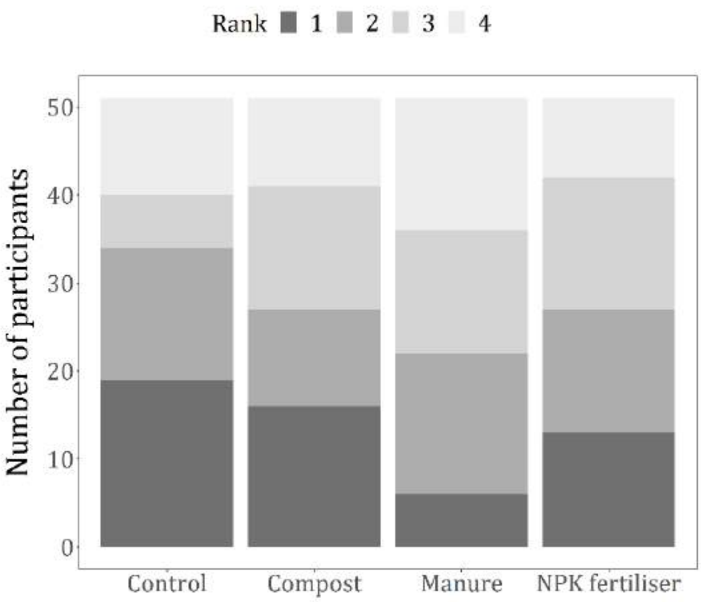

Figure 4.6 | Overview of how tubers from different treatments got ranked among each other, with '1' indicating a participant's favourite sweet potato slice, and '4' indicating a participant's least preferred slice.

4.3.2.7 Relationships between treatments, soil quality and tuber yields

Using structural equation modelling I analysed how treatments influenced the amount of soil available nitrogen, phosphorus and potassium, and soil moisture, and how these variables then influenced tuber yields. This analysis therefore had the advantage of directly testing the supposed causal structure of the effects of treatment on yield. The SEM fitted adequately to the data (Fisher's C = 25.52 with $p = 0.11$ on 18 degrees of freedom). The effect of treatments on soil chemical properties and soil moisture confirmed the above-described analyses. Increased plant biomass (as calculated by the total of leaf, vine and tuber yield) decreased soil moisture. Compost and NPK fertiliser also affected soil moisture via additional pathways. Of all soil properties, higher levels of soil available nitrogen had a positive effect on tuber yields, while higher levels of soil moisture decreased tuber yields (Fig. 4.7). Thus, the SEM indicated that the main path by which treatments affected yield was through increasing available nitrogen and reducing soil moisture. It also suggested that treatment-induced increases in available phosphorus and potassium did not directly affect tuber yield.

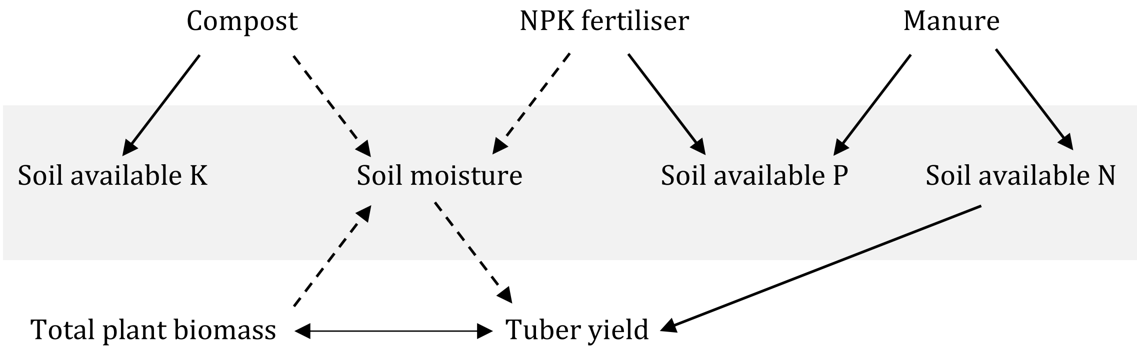

Figure 4.7 | Graphical depiction of the structural equation model with ⟶ indicating a positive correlation, and ⇢ a negative correlation with $p < 0.05$. Compost increased the amount of soil available potassium, NPK fertiliser and manure the amount of soil available phosphorus, and manure also the amount of soil available nitrogen. An increase in total plant biomass decreased soil moisture. Compost and NPK fertiliser also decreased soil moisture via additional pathways. Soil moisture and soil available nitrogen directly influenced tuber yields, with soil available nitrogen having a positive effect while soil moisture having a negative effect. For full results, see Appendix B, Table 15.

4.4 Discussion

I found that using banana peel compost, chicken manure and NPK fertiliser affected soil nutrient status, soil moisture and sweet potato yields and quality, and that these effects differed between new gardens and fallowed gardens. Overall, NPK fertiliser had the largest positive effects.

4.4.1 Effect of treatments on soil properties

The amount of nitrogen, phosphorus and potassium in the soil fell within the range of values previously recorded in new and fallowed gardens in PNG (Sillitoe, 1996; Fujinuma *et al.*, 2018;

Kukla *et al.*, 2019). The level of available and total nitrogen in Ohu was relatively low compared to other regions in PNG, whereas the amount of available and total phosphorus was average. The amount of available potassium was high compared to Highland sites (Sillitoe, 1996; Fujinuma *et al.*, 2018), but low compared to other Lowland sites (Kukla *et al.*, 2019).

Treatments increased the amount of available nutrients in the soil, with the increases corresponding to their different inputs. Compost increased the amount of available potassium, which was expected since banana peels contain high levels potassium and low levels of nitrogen and phosphorus. Chicken manure increased the amount of available nitrogen and phosphorus, which again followed expectations. NPK fertiliser, which is high in phosphorus, increased the amount of available phosphorus in new gardens and total phosphorus in new and fallowed gardens. Since NPK fertiliser also contains large amounts of nitrogen I expected soil available nitrogen to increase as well, but this was not the case. It is likely that the available nitrogen provided by NPK fertiliser was taken up by the sweet potato plants before soil measurements were taken at the end of the cropping period, which is probably why I did not find an effect of NPK fertiliser on soil available nitrogen. NPK fertiliser plots had an average increase in leaf, vine and tuber yields of 356 grams per mound (7.3 t/ha) compared to control plots. Estimated nitrogen removal by sweet potato vines and roots for this increase is 32 kg N/ha (O'Sullivan, Asher and Blamey, 1997), which is close to the 40 kg/ha of fertiliser which I applied.

Soil moisture levels were relatively high compared to levels recorded in the fields of shifting farmers in Madagascar (Gay-des-Combes *et al.*, 2017) and Bangladesh (Miah *et al.*, 2014). PNG is one of the wettest places in the world, and thus these high soil moisture levels are not surprising (The World Bank Group, 2021). At the start of the experiment, levels of soil moisture were higher in fallowed gardens compared to new gardens. This was expected, as measurements were taken 1-2 weeks after the vegetation in fallowed gardens had been cut, whereas in new gardens removal of vegetation had happened 1-2 months earlier, allowing the soil to dry out more (Miah *et al.*, 2014). However, over the cropping seasons I found that mounds in fallowed gardens had lower soil moisture levels compared to new gardens. Atchley *et al.* (2018) found that fires of low to moderate burn severity, as applied in new gardens, within a year will result in increased soil water due to a reduction in evapotranspiration, which could explain the higher levels of soil moisture in new gardens. Applying banana peel compost, chicken manure and NPK fertiliser decreased soil moisture, with compost reducing soil moisture in fallowed gardens, chicken manure in new gardens and NPK fertiliser in both new and fallowed gardens. These results can in part be explained by the fact that treatments increased the yields of leaves, vines or tubers, causing the plants to take up more water from the soil and increasing the amount of water lost through transpiration (Bourke and Harwood, 2009). However, as shown in the SEM, compost and NPK also decreased soil moisture via additional pathways, which was unexpected and I can only speculate about the underlying mechanisms. It may have been that compost and NPK fertiliser improved soil structure, and soils with better structures have larger volumes of macropores that drain more easily (Weil and Brady, 2017). Decayed organic matter is known to increase soil porosity (Kranz *et al.*, 2020). NPK fertiliser may have increased soil macroporosity by increasing the number of sweet potatoes, which enhances rooting depth and root proliferation, and roots are able to increase soil porosity (Scholl *et al.*, 2014). Increased volumes of macropores may have caused water to drain from the mounds deeper into the soil, and with that allow compost and NPK fertiliser to reduce volumetric soil moisture in the mounds.

4.4.2 Effect of soil treatments on sweet potato yield

In control plots the mean tuber yield per mound was 313 grams, or 6.4 t/ha. Worldwide, the average yield of sweet potato in 2019 was 12 t/ha, and in PNG 5.1 t/ha (FAO, 2021b). Thus, sweet potato yields reported here are relatively high for PNG standards, but low compared to global standards and could thus potentially be increased.

My results show that one way to achieve this is by applying soil treatments, including chicken manure and NPK fertiliser (but not compost). How well a treatment performed in terms of increasing tuber yield depended on whether a garden was new or fallowed, with chicken manure only having an effect in fallowed gardens. This may be explained by the fact that organic fertilisers, including chicken manure, need to be broken down by micro-organisms before their nutrients can be taken up by plants (Amanullah, Sekar and Muthukrishnan, 2010). The fire that is used to prepare new gardens reduces bacterial and fungal populations in the soil (Miah *et al.*, 2014), which may, temporarily, decrease the effect of organic fertilisers. NPK fertiliser, on the other hand, can be taken up directly by plants (Heeb *et al.*, 2006), and could thus increase yields in both new and fallowed gardens.

One of the main pathways through which treatments affected yield in my experiment was through increasing available nitrogen. This is not surprising given that the amount of nitrogen in the soil in Ohu was low. Nitrogen has been shown to increase leaf area, which in turn increases mean tuber weight and hence tuber yield (Bourke, 1985). However, too much nitrogen can cause luxuriant growth of vines at the expense of storage root yield. Therefore, recommendations for application of nitrogen fertilisers to sweet potato generally lie between 30 and 90 kg N/ha (O'Sullivan, Asher and Blamey, 1997), and my application of 40 kg N/ha falls within these bounds. I expected potassium to influence sweet potato yields as well, but I did not find evidence for this. This may be because the amount of available potassium in Ohu was well above the critical threshold for sweet potato of 31 mg/kg (Nicholaides III *et al.*, 1985), and further increases may not improve yields. Phosphorus also did not influence yields. The threshold for deficiency of phosphorus levels for sweet potato has been estimated to range from 5 to 7 mg/kg (O'Sullivan, Asher and Blamey, 1997). The phosphorus levels in the soils in Ohu were above this threshold, which explains why phosphorus did not affect yields.

The other pathway through which treatments affected yield was through soil moisture. Soil moisture has been shown to have an important effect on sweet potato tuber development (Gajanayake *et al.*, 2013) with both water deficits and excesses decreasing tuber yields (O'Sullivan, Asher and Blamey, 1997). Volumetric soil moisture levels of 17-20% have been found to be optimal for root development (Gajanayake *et al.*, 2013), and soil moisture levels in compost, chicken manure and NPK fertiliser plots were closer to this optimal level than in the controls, where the level of soil moisture was recorded to be an average of 30%.

Application of banana peel compost caused tubers to be less likely to be suitable for human consumption. Compost made from the grass *Ischaemum polystachyum* has been shown to improve sweet potato yields by increasing tuber initiation rather than promoting tuber bulking (Sillitoe, 1996), and I find the same here; compost treatment decreased the average weight of tubers, especially in new gardens. If tubers are too small, farmers will deem them unsuitable for human consumption, and are likely to feed the tubers to their livestock instead (Sillitoe, 1996).

Application of chicken manure decreased the taste of tubers. The application of chicken manure may have increased the water content of roots making the tubers taste less sweet (Sowley, Neindow and Abubakari, 2015) and increased the production of non-tuberous roots on its skin (Magagula *et al.*, 2010). Especially in Ohu where food is not in critically low supply, taste may be an important consideration for farmers when deciding to adapt a fertiliser.

4.4.3 Looking forward

I found that soil moisture and available nitrogen play an important role in determining sweet potato yields. Farmers in PNG already employ strategies to optimise these factors. For example, they often plant sweet potatoes in mounds, which allows excess moisture to drain away from the root zone (Bourke and Harwood, 2009). In parts of the Highlands where sweet potato is an especially important food crop, farmers rotate sweet potato with leguminous crops such as peanut or winged beans which can increase soil nitrogen levels (Bourke and Harwood, 2009).

My study shows that in the Lowlands it is also possible to enhance soil quality and yields using nitrogen-containing fertilisers such as chicken manure and NPK fertiliser, with their relative effectiveness depending on whether the garden is new or fallowed. I expect other fertilisers, which are also capable of increasing available nitrogen and reducing soil moisture, to increase yields too, but this would need further research. Alternative fertilisers may be more appropriate in places where soil properties differ.

In Ohu, out of banana peel compost, chicken manure and NPK fertiliser, NPK fertiliser came out as the best option as it was the only fertiliser that increased yields in both new and fallowed gardens. Unlike chicken manure, NPK fertiliser produced tubers which taste similarly good compared to tubers from control plots. The use of NPK fertiliser was also financially profitable in Ohu (Appendix B, Table 16), although only marginally so and only makes a real difference if farmers sell large quantities of sweet potato. However, excessive use of NPK fertiliser can have negative effects on the environment, including eutrophication and contamination of aquatic systems, soil acidification and a reduction of plant species richness in neighbouring herbaceous communities (Shoji *et al.*, 2001; Soons *et al.*, 2017). Here I applied nitrogen and phosphorus at a rate of 12 g/m^2/year, which is unlikely to have a significant negative effect on biodiversity (Soons *et al.*, 2017), but it will be important to monitor possible negative consequences of NPK fertiliser in this context, especially when it is used over longer time periods.

Whether the use of fertilisers can enhance the lifetime of a garden, will depend on multiple factors. At the moment, farmers in Ohu leave their gardens to fallow despite adequate sweet potato yields. This may at first seem surprising given that starting a new garden requires significant labour and time inputs (Sillitoe, 1999). However, sweet potatoes are known to produce adequate yields on soils that may be too poor for other crops (O'Sullivan, Asher and Blamey, 1997), so farmers may choose to fallow a garden so they can grow a variety of crops rather than just sweet potato. In addition, it may be that in fallowed gardens the pressure from weeds, pests and diseases become too high, reducing the return to labour ratio and thus making it worthwhile to switch to a new garden (Sirén, 2007). Especially in Ohu, starting a new garden is relatively easy compared to other regions in PNG as people mainly cut young secondary forest and they do not fence their gardens against pigs, which can promote the quick turnaround in gardens. If soil quality is improved and yields enhanced, yields may outweigh labour inputs for longer, which could potentially encourage farmers to prolong the lifetime of their garden but this would need to be confirmed.

Currently, farmers in Ohu are typically not using compost, animal manure or NPK fertilisers in their food gardens. Using fertilisers requires additional knowledge, more work such as having to acquire and transport materials to gardens, and in the case of NPK fertiliser also money, which are barriers to taking-up these practices (Zhang, Matous and Tan, 2020). However, in Ohu there is great interest in these techniques as farmers are seeing their fallow times, soil fertility and yields decline.

4.5 Conclusion

Social-ecological changes, including demographic and political transitions, are putting pressure on the existing swidden system. This research shows that locally available fertilisers can improve soil quality and enhance the yields of swidden farmers: chicken manure increased sweet potato tuber yields in fallowed gardens, as did banana peel compost although this result was not statistically significant. NPK fertiliser increased yields in both new and fallowed gardens, produced tubers of similar quality and taste to control plots and was financially profitable, and hence came out as the best option. Treatments affected yield through increasing available nitrogen and reducing soil moisture. Farmers were keen to consider modifying their current soil management practices, provided they had more information on how to use these fertilisers. Thus, there is both feasibility and scope for swidden farming to be adapted in the Lowlands of PNG, so that it can continue to be a viable and sustainable way of farming and living.

- Chapter 5 -

Quantifying unintended effects of an agroecological research project on farmers' practices and social network in Papua New Guinea

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Posing for a photograph in Ohu, Papua New Guinea.

'No matter what, expect the unexpected. And whenever possible BE the unexpected.'

- Lynda Barry

Abstract

1. Agroecological researchers and advocates often make assumptions about the social impact and dissemination of their work: researchers may assume that their work has impact through post-research dissemination, while advocates may assume that new agroecological practices can be effectively spread through existing social networks.
2. Here I test these assumptions by quantifying the effects of an agroecological research project on farming practices and the social network in a village community in Papua New Guinea. The project aimed to test the effect of applying banana peel compost, chicken manure and NPK fertiliser on sweet potato yields. Local farmers were involved in the research as project garden owners or research assistants. Using stochastic actor-oriented modelling, I tracked changes in farming practices and the social network.
3. Over the course of the research project, more people started to use food waste on their farms, while animal manure and NPK fertiliser were not frequently adopted. Farmers also took up behaviours that were not directly researched, such as mulching and planting the specific variety of sweet potato that was used in the project. This suggests that local farmers created meaning from the project, despite the researchers not intending to give advice until the end of the project.
4. The research project also affected the community's social network. Research assistants became more often sought-after for advice, while knowledge about the project did not flow far from those directly involved. These results indicate that who gets involved in a project may have social consequences, and show the importance of understanding existing social networks before they are relied upon for spreading farming practices.
5. Overall, this work challenges often-held assumptions about the social impact and dissemination of agroecological research, provides insights into the types of agricultural innovations more likely to be accepted among farmers, and explores how new practices may most effectively be promoted within a community.

5.1 Introduction

Agroecology aims to solve challenges in agricultural production. To achieve this, different approaches are taken, with 'agroecology' not only being an agricultural practice, but also a scientific discipline and a social movement (Wezel *et al.*, 2009). Agroecological researchers focus on investigating factors affecting agricultural production, while agroecological advocates use agroecology to drive forward a political agenda on sustainable agriculture, rural development and environmentalism (Wezel *et al.*, 2009).

Agroecological researchers often work in collaboration with farming communities and spend a significant amount of time 'in the field' to collect their data. It is often assumed by these researchers that their work may impact farmers' practices, but only at the end of a project (Bertuol-Garcia *et al.*, 2018). Much of the literature on how to bridge the so-called science-policy gap also stresses the importance of communication, dissemination and implementation once the research is done (Toomey, 2016). However, some have begun to question the supposedly linear relationship between science and society, arguing that it does not adequately recognise the complex interactions that exist in the spaces and places in which research takes place, especially when the research is field-based (van Kerkhoff and Lebel, 2015). For example, Hakkarainen *et al.* (2019) describe how local fishermen thought of ways of making their fishing business more profitable, based on information collected by a researcher, despite the researcher not intending to give advice about this. Ideas of linear knowledge transfer are increasingly replaced by more complex understanding of knowledge exchange in which research is embedded in society, and has impact not only upon its completion but also during the research process (Toomey, Knight and Barlow, 2017).

There are very few studies that pay attention to the encounters that occur between researchers and non-scientists during field research (Toomey, 2016). It is, however, important to better understand the impacts of the scientific process, as it can affect the lives of local people (Beaman and Dillon, 2018; Brittain *et al.*, 2020), influence the acceptance of research results by local actors (Toomey, 2016), and affect the long-term acceptance of research activities in a community (West, 2006). Positive or negative effects of a research project can have far-reaching consequences for local society and the environment, and thus need to be understood (Shackleton, Cundill and Knight, 2009). This is especially true when subsistence resource users are involved, because they make important decisions which affect the dynamics of their natural resources and have consequences for their own food security and biodiversity conservation (Shackleton, Cundill and Knight, 2009).

Contrary to researchers, agroecological advocates who promote the use of agroecological practices by farmers, aim to have impact from the onset of a project. Usually agroecological extension officers target specific farmers within a community and provide them with training on new agroecological practices (Beaman and Dillon, 2018). These farmers are then expected to influence their wider community (Genius *et al.*, 2014). Whether this works, and which farmers could best be targeted, depends on the information-sharing relationships among farmers (de Lange, Milner-Gulland and Keane, 2019).

Social network analysis has emerged as a suitable tool to investigate the structures and properties of an information-sharing network (Groce *et al.*, 2018). Few empirical studies directly address how social networks affect natural resource management in rural settings of the Global South (Groce *et al.*, 2018). This is likely to be due to the difficulty of obtaining appropriate data in such settings, and potentially lack of access to the complex modelling tools that such data often require (Matous and Todo, 2015). However, it is crucial to have a solid understanding of social networks among smallholder farmers as it helps agroecological extension officers to know how social networks can be relied upon for effectively spreading information and how changing farming practices may be achieved (Matous and Todo, 2015; Groce *et al.*, 2018). It is also important to find out how agroecological researchers and advocates may be affecting local networks and the processes that take place within them as a side effect of their activities, so that potential unintended negative effects can be avoided.

Here I report on the effects of an agroecological research project on farming practices and the social network in a village community in Papua New Guinea (PNG). The research project aimed to investigate whether the use of fertilisers could increase the yields of swidden farmers (Hazenbosch *et al.*, 2021). To achieve this, the research team established experimental plots on the fields of swidden farmers, applied locally available fertilisers, and tracked soil quality and crop yields of sweet potato for 12 months. Depending on which fertiliser yielded the best results at the end of the experimental trial, the research team intended to inform local farming practices after the work had finished. However, I observed that even while the research took place, farming practices and information-sharing practices among local farmers were changing. I conceptualised the setting as a network system, and tracked and quantified the joint evolution of farming practices and the social network. I estimated the underlying processes through simulations using stochastic actor-oriented modelling. The results challenge often-held assumptions by agroecological researchers and advocates. They also help explore what type of agricultural innovations are likely to be accepted among farmers in this setting, and how practices may be most effectively promoted within a community.

5.2 Materials and Methods

5.2.1 Context

In February 2018, together with a team of Papua New Guinean researchers, I entered Ohu village (S 05°13.081', E 145°40.735') to conduct scoping research on soil quality and crop yields. Ohu has hosted various research projects since 1995, and has a long-standing collaboration with The New Guinea Binatang Research Centre (NGBRC), a local non-profit organisation committed to conducting biological research and conservation. In August 2018, the research team was granted permission from local leaders to set up experimental gardens. Ten gardens were established on the land of local farmers. Some farmers were involved in the research project as project garden owners or research assistants. Project garden owners were actively involved in monitoring of the gardens, whereas research assistants contributed to preparing and harvesting the gardens. The local assistants came from four different clans, out of a total of 11 clans which make up Ohu village. In the experimental gardens the effect of different soil enhancement techniques, including applying banana peel compost, chicken manure and commercial NPK fertiliser on soil quality and crop yield were tested. Traditionally, farmers in Ohu do not use these fertilisers in their food gardens (Hazenbosch *et al.*, 2021). Sweet potato (*Ipomoea batatas*) was chosen as the focal crop as it is a staple in PNG (Bourke and Harwood, 2009). I asked a local farmer to select a suitable variety of sweet potato, which the team could grow in the experimental gardens. The farmer selected one variety locally called 'wan mun kaukau'. It later turned out that the farmer did not have much experience growing this specific variety, so was keen for me to try it. The experimental gardens were actively used for research throughout the following year. To my knowledge, no other agriculture-related projects were conducted in Ohu from 2018 to 2019.

5.2.2 Survey

To track changes in farming practices and the community's social network, I administered two waves of interviews, one at the beginning of the research project and one at the end. The first wave was conducted in November and December 2018, before the first harvest of the experimental gardens. The first wave of interviews cannot be considered a true pre-project baseline. But given that the interviews took place before the results of the first harvest were collected, I assume that people were not changing their farming practices yet as a result of my findings and that the research project had had a minimal influence on the social network thus far. Even if there had already been some effects, I would be underestimating rather than overestimating the overall impact of the research project on local farming practices and the social network. The second wave of interviews was conducted after the final harvest of the experimental gardens in July and August 2019, with three final interviews being conducted in October 2019 due to unavailability of the participants in earlier months.

The team collected data from 63 people across the four clans in Ohu that were involved in the research project (Table 5.1), which represents ~80% of the household heads in these clans. I interviewed both the male and female head of each household, because in PNG men and women farm together on shared fields and are thus both agricultural decision-makers (Pamphilon and Mikhailovich, 2017). The four clans live on geographically neighbouring land. I had to exclude interview data from six farmers, either because during the second survey they were no longer present in the village (two people) or they did not want to take part in the second interview (four people). Free prior-informed consent was given by all participants before the start of the interviews. The interview protocol was approved by the University of Oxford's Research Ethics Committee under permit number R58337/RE002.

Table 5.1 | Description of the sample. Total sample size consisted of 57 participants.

	Non-participants	Project garden owners	Research assistants
Number of people	33	10	14
Age (mean)	42	40	38
Gender (no. of ♀)	17	6	3
Clan 1 (no. of people)	7	4	0
Clan 2	16	1	3
Clan 3	9	5	10
Clan 4	1	0	1

Interviews were done face-to-face in Tok Pisin (PNG's lingua franca) using fixed-form data sheets by my research team from NGBRC and myself. In the first part, I collected demographic information, such as age, gender, clan and main livelihood of the interviewee. I also recorded Global Positioning System coordinates of the interviewee's house so I could calculate the shortest distance in metres between houses of respondents. People in Ohu can walk from one house to the next in more or less a straight line, so I did not apply any transformations when calculating distances between two points.

Next, I recorded the interviewee's farming practices. Some of the farming practices I asked about, including the use of food waste, animal manure and NPK fertiliser, were directly associated to my research project. Food waste corresponded to my banana peel compost treatment, animal manure to my chicken manure treatment and NPK fertiliser to my NPK fertiliser treatment. Others, including the use of grass, leaves or plant residues besides food waste (henceforth called mulch), were related to my research project, but not specifically tested in the experimental gardens. I asked about both directly associated and related farming practices to better understand the potential unintended effects of the research project on farming practices.

In the third part of the survey, I collected data on farmers' most important information sources regarding their food gardens. Specifically, the English translation of the network prompt was: 'Now we need you to think about people in the village you have talked to most often about farming over the last year. Could you give us the names of up to five people who you regularly talk to about your food gardens?'. The elicited networks were preserved in their directed form. This allowed me to distinguish between information seekers, conceptualised as nominating many others (i.e. actors with a high out-degree in network science terminology), from popular advisors, conceptualised as often being nominated by others (i.e. actors with a high in-degree). Network analysis requires setting a meaningful boundary. In this study the boundary of the network is the clans that were involved in the research project. I only considered links within the selected boundary and discarded outgoing links, as is usually done within network analyses.

In the second interview wave, there was a fourth part to the interview in which I asked participants about why or why not they were using a certain farming practice, whether they had changed the variety of sweet potato that they were planting, and whether and what they had learned from the research project (Table 5.2).

Table 5.2 | Overview of variables. Variables highlighted in blue are independent variables, and unhighlighted variables are dependent variables. Note that in the research project only three farming practices, namely those related to food waste, animal manure and NPK fertiliser, were researched. The other two farming practices, including mulching and the variety of sweet potato planted, were not explicitly researched.

Variable	Description of variable	Metric
Time	Indicates whether the interview was conducted before or after the research project had been conducted.	Factor Time 1 | Time 2
Project	Describes whether someone was involved in the research project, involved as a project garden owner or involved as a research assistant.	Factor Not involved | Project garden owner | Research assistant
Gender	Specifies whether the interviewee identified as a man or a woman.	Factor Man | Woman
Age	Indicates the interviewee's age in years in 2019.	Continuous
Location	Shortest distance in meters between houses of respondents.	Continuous
Clan	Describes the clan the interviewee was part of.	Factor Clan 1 | Clan 2 | Clan 3 | Clan 4
	Researched behaviours	
Food waste	Specifies whether respondents applied food waste on their plots.	Factor No | Yes
Animal manure	Specifies whether respondents used animal manure.	Factor No | Yes
NPK fertiliser	Specifies whether respondents used NPK fertiliser.	Factor No | Yes
	Not researched behaviours	
Mulching	Specifies whether respondents used mulching.	Factor No | Yes
Variety	Specifies if after the research project had been conducted (time 2), respondents started planting the specific variety of sweet potato planted in the experimental gardens.	Factor No | Yes
	Information dissemination	
Learned	Whether respondents stated that they had learned something from the research project (at time 2).	Factor No | Yes

	Network	
In-degree	In-degree is the number of people in the network that identified the focal respondent as an information source for farming.	Continuous
Out-degree	Out-degree is the number of people named by the focal respondent as information sources for farming.	Continuous

5.2.3 Statistical analyses

The main aim of the analyses was to determine how the research project affected farmers' behaviour and social network. These can be interconnected, though, with people who exchange information being more likely to display similar behaviour (i.e. social influence), and people behaving similarly having a higher chance of forming friendships (i.e. social selection) (Snijders, van de Bunt and Steglich, 2010). To analyse the joint evolution of farmers' behaviour and social network, I conducted stochastic actor-oriented modelling (SAOM) (Snijders et al., 2010) in R version 4.0 (R Core Team, 2020). For a full explanation of SAOM, see Appendix C, section 1.

In short, a SAOM is based on the assumption that the network evolves as a stochastic process that is driven by its actors, in my case the farmers whom I interviewed. A SAOM models the change between two observed periods, such as between a first and second wave of interview data. Between these two observation moments, actors receive chances to change the ties in their network in a random order. Actors can also choose to increase, decrease or maintain their level of behaviour. SAOMs allow the specification of 'effects' which represent ways in which network structures and covariates affect the network or behaviour. Examples of effects include the 'reciprocity effect', which represents the tendency to reciprocate ties, or the 'attribute alter' effect, which indicates whether actors with higher values for an attribute (e.g. participation in the research project) receive more nominations from others. The strength of each effect is estimated using a simulation-based approach (Ripley *et al.*, 2019). The parameter represents the log-probabilities of change, similar to parameters of multinomial logistic regression models.

In my case the main effects included: (1) the effect of participation in the research project on the network, and (2) the effect of participation in the research project on farming behaviours and information dissemination. To test whether the network and farming behaviour were interconnected, I also included (3) the effect of farming behaviours on the network, and (4) the effect of the network on farming behaviours and information dissemination. Lastly, I included (5) standard structural network effects which represent basic structures of networks, and (6) effects of geographical distance between farmers, clan, gender and age on the network, as they have been shown to influence networks (Matous, Todo and Mojo, 2013; Matous and Todo, 2015; Beaman and Dillon, 2018; Simpson, 2020). Participation in the research project was coded as 0 for non-participation and 1 for participation either as a project garden owner or research assistant. Including project garden owner and research assistant as separate levels led to over-specification of the model and was thus avoided. The researched farming behaviours of using food waste, animal manure or NPK fertiliser were grouped into one variable called 'Total researched behaviours' with people who used any of these behaviours scored as 1, and those who did not scored as 0. This was because too few people adapted animal manure or NPK fertiliser over the course of the project and including them as separate behaviours led to non-convergence. A full list of the effects included and their descriptions is provided in Appendix C, Tables 1 and 2, with code deposited at: https://data.mendeley.com/datasets/ft8gb8cn5b/1.

The full SAOM with both network and behaviour data showed that there were no significant relationships between farmers' social network and behaviour (Appendix C, Table 3). This allowed me to analyse the network data and behaviour data separately and more in depth. To better understand the structure of the social network I re-ran the SAOM, but with only the network part, which included: (1) effects of participation in the research project on the network, (2) standard structural network effects, and (3) effects of geographical distance between farmers, clan, gender and age on the network. This time I coded participation as a dummy variable in which I represented non-participants, project garden owners and research assistants separately (Appendix C, Table 2).

To further understand the effect of the research project on farmer behaviour and information dissemination I used logistic regressions. The use of food waste, mulching, starting to plant the research project's specific variety of sweet potato and having learned from the project were the dependent variables. Participation in the project as non-participant, project garden owner or research assistant was an independent variable. I included an interaction between participation and time in the case of using food waste or mulching. For starting to plant the project's specific variety of sweet potato and learning, time was not included as these were only relevant during the second survey. Gender was also included as an independent variable, as the adoption of behaviours may differ between men and women (Farnworth *et al.*, 2016). Including two data points from the same household leads to pseudo-replication, so I included household number as a random effect. However, model results did not significantly change (Appendix C, Table 4), so I report here on the simpler model without household number as a random effect. For a full overview of the models run, see Appendix C, Table 5.

A general linear model with a binomial error structure was fitted to the data using the 'glm' function in R. I checked for over-dispersion by calculating the ratio between residual deviance and degrees of freedom. If the ratio was > 1.2 or < 0.8 the model was re-fitted with a quasi-binomial distribution. I report values from the full models because I only included a few unrelated independent variables and thus model simplification was unnecessary. These models were not run for the behaviours of using animal manure and NPK fertiliser, as there was too little variation in the data, thus running statistical analyses would be inappropriate. Instead, the results for these behaviours are described qualitatively.

5.3 Results

Results from the experimental gardens showed that using NPK fertiliser and chicken manure, but not banana peel compost, improved soil quality and enhanced sweet potato yields (Hazenbosch *et al.*, 2021). The effect of mulching and the variety of sweet potato planted were not researched.

5.3.1 *Changes in farming behaviour*

Before the start of the research project, the researched behaviours were not used by many farmers: 19% of farmers used food waste in their gardens, 5.3% animal manure and none NPK fertiliser (Table 5.3). Mulching, however, was a popular practice among 72% of the farmers, especially women (Table 5.4). There was a tendency, significant at the $p < 0.1$ level, for project garden owners to use food waste and research assistants to use mulching compared to non-participants (Table 5.4).

Farmers' behaviour changed over time (Table 5.3). For the researched behaviours, there was a significant increase in the number of farmers who used food waste during the second survey (Table 5.4). Whether people started to use food waste was not linked to their involvement in the research project, as project garden owners and research assistants were not more or less likely to adopt these practices compared to non-participants (Table 5.4). Farmers did not use animal manure or NPK fertiliser more often during the second survey. Farmers gave as their main reason for this that they lacked knowledge about how to apply these fertilisers. In addition, farmers mentioned that they may not have access to animal manure or NPK fertiliser, that using these techniques was too much extra work, or that they were afraid that using these fertilisers may negatively affect their physical health.

There was an increase in the uptake of behaviours that were not explicitly researched during the project (Table 5.3). Significantly more farmers started to mulch. Similarly to the use of food waste, whether people started to mulch was not dependent on their involvement in the research project (Table 5.4). Some farmers started to plant the specific variety of sweet potato that was also planted in the experimental gardens. Research assistants were more likely than non-participants, and women were more likely than men, to start planting the project's variety of sweet potato (Table 5.4).

All project garden owners and 13 out of 14 research assistants said that they had learned from the research project, which was significantly higher than non-participants. Those who had learned something said that they had learned that food waste, animal manure and NPK fertiliser can be used to enhance soil quality, and how to apply these fertilisers. Four people also mentioned that they now knew how to better manage their land.

Table 5.3 | Change in farming behaviours. Numbers of respondents using a specified practice at time 1 and time 2 are displayed. Total sample size consisted of 57 participants.

	Non-participants		**Project garden owners**		**Research assistants**	
Researched behaviours						
	Time 1	*Time 2*	*Time 1*	*Time 2*	*Time 1*	*Time 2*
Food waste	4	14	4	5	3	3
Animal manure	0	6	2	1	1	1
NPK fertiliser	0	0	0	0	0	1
Non-researched behaviours						
Mulching	21	28	9	8	11	13
Variety		2		1		5
Information dissemination						
Learned		7		10		13

Table 5.4 | Dynamics of farming behaviour and information dissemination from time 1 to time 2. ns = non-significant, (+)/(-) = $p < 0.1$, +/- = $p < 0.05$, ++/-- = $p < 0.01$, +++/--- = $p < 0.001$, with + indicating a positive effect and - a negative effect. Reference levels are given in grey shading for each variable. For full results, see Appendix C, Table 6.

		Food waste	**Mulching**	**Sweet potato variety**	**Learned**
Project	Non-participant				
	Project garden owner	(+)	ns	ns	+++
	Research assistant	ns	(+)	++	+++
Time	Time 1				
	Time 2	++	+		
Gender	Man				
	Woman	ns	+++	+	ns
Project * Time	Non-participant : Time 1				
	Garden owner : Time 2	ns	ns		
	Research assistant : Time 2	ns	ns		

5.3.2 Changes in the social network

The structure of the social network among farmers in Ohu was sparse and clustered, and dynamic between the two time points (Table 5.5 and Fig. 5.1). Both during the first and second survey people considered, on average, one to two other people as important sources of information when it comes to farming (Table 5.5). However, some did not find anyone in the group to be an important source, while one person nominated five people. Similarly, the typical person was considered an important source of information on farming by one to two other group members. Again, some people were not nominated while one person was nominated by seven other people. The network also was highly dynamic. Out of the 88 bonds mentioned during the first survey only 54 were still present during the second survey, and 56 new bonds were formed (Table 5.5).

Table 5.5 | Properties of the network.

	Time 1	Time 2
Total number of ties in the network	88	110
Network density	0.028	0.034
Mean in/out-degree	1.5	1.9

The network was characterised by a flat structure in which there were no clear opinion leaders. The strong negative outdegree effect indicates that farmers were not inclined to form bonds with others. Farmers were primarily keen to engage in bi-directional exchanges and to share information within closed clusters, as indicated by the positive reciprocity and transitive ties effects (Table 5.6). People were more like to form a bond with someone who lived close to them or who was from the same clan (Table 5.6). There was a tendency, significant at the $p < 0.1$ level, for men to form bonds with other men and women with women (Table 5.6).

The main change in the network from the first to the second survey was related to participation in the research project. Those farmers who were selected as research assistants were more sought-after by others for farming advice compared to non-participants at the time of the second survey compared to the first survey (Table 5.6). Project garden owners, however, did not get nominated more often during the second survey compared to the first.

Table 5.6 | Dynamics of the network. (+)/(-) = p < 0.1, +/- = p < 0.05, ++/-- = p < 0.01, +++/--- = p < 0.001, with + indicating a positive effect and - a negative effect. The estimate shows the change between the two surveys in the effect of the variable. Here I display only the effects of interest. For a table of the full model and the model's goodness of fit, see Appendix C, Table 7.

	Description	Estimate	Standard error	p-level
	Structural network effects			
Outdegree	Overall information-seeking activity	-2.3746	0.7073	---
Reciprocity	Mutual information exchange	1.7578	0.3358	+++
Transitive ties	Clustering of information network	0.6821	0.2078	++
Distance	Geographical proximity influences tie formation	-0.0020	0.0005	---
Same clan	Preference for advisors from same clan	0.8106	0.3290	+
Gender with ♀ = 1				
• Ego	Tendency for women to seek more information	0.2510	0.3154	
• Alter	Preference for female advisors	-0.5416	0.2746	-
• Same	Preference for advisors from same gender	0.4663	0.2501	(+)
Project garden owner				
• Ego	Tendency for project garden owners to seek more information	-0.1309	0.4287	
• Alter	Preference for advisors who are project garden owners	0.2593	0.4260	
• Same	Preference of project garden owners toward project garden owners	-0.0936	0.4159	
Project research assistant				
• Ego	Tendency for research assistants to seek more information	0.4926	0.3689	
• Alter	Preference for advisors who are research assistants	0.8816	0.3349	++
• Same	Preference of research assistants toward research assistants	-0.2459	0.2491	

Time 1 / Time 2

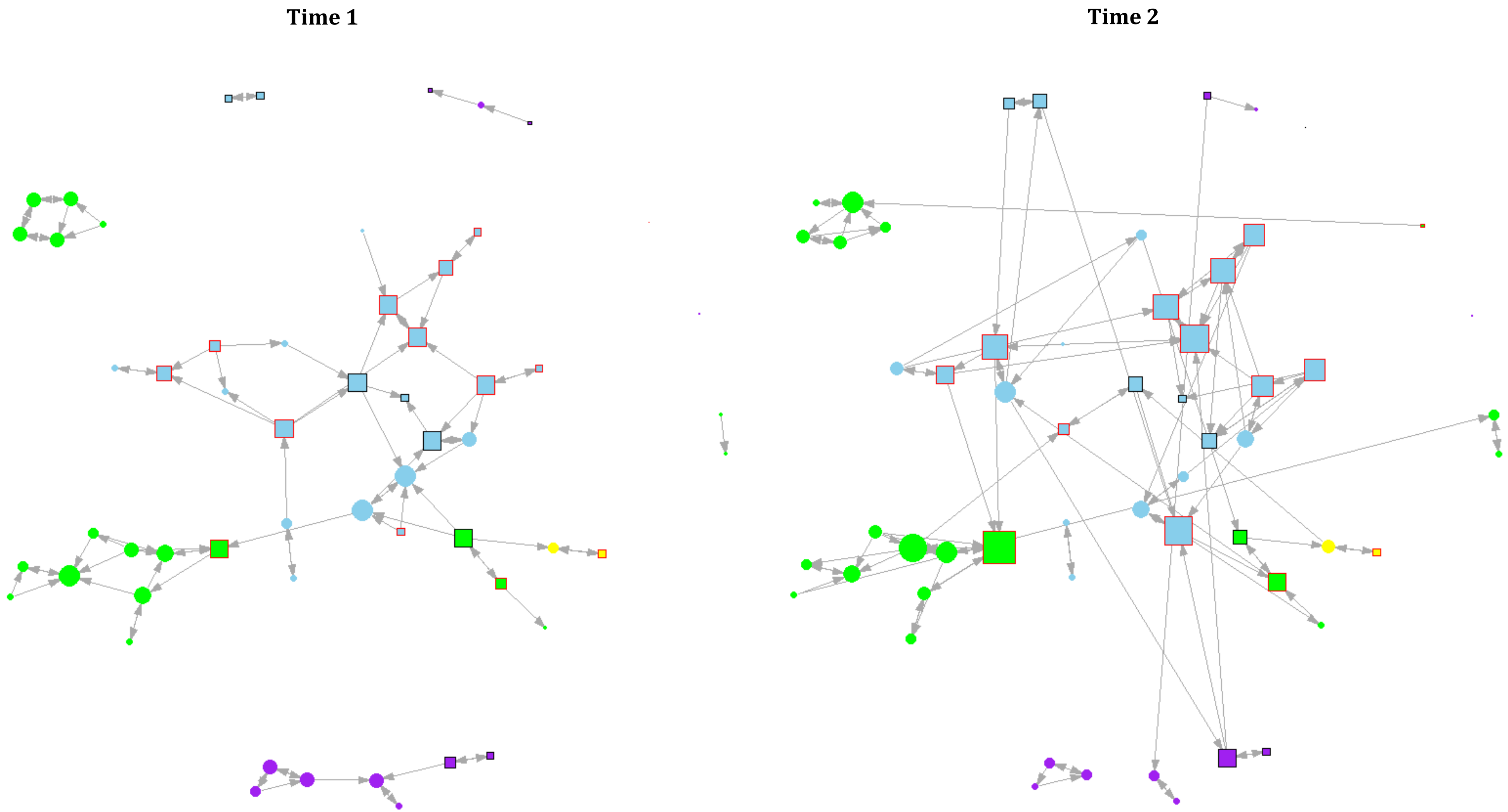

Figure 5.1 | Visualisation of the social network at time 1 (left) and time 2 (right). Each node represents an actor in the network with the size of the node representing the importance of the actor based on their average in/out-degree. Each arrow represents a link and points from a respondent to an important source of information. The colours indicate different clans with clan 1 being purple, clan 2 green, clan 3 blue and clan 4 yellow. Circles indicate non-participants, whereas squares represent nodes who were involved in the research project, with squares with black borders indicating project garden owners and squares with red borders indicating research assistants.

5.4 Discussion

While the agroecological research project was ongoing, local farming practices and the community's social network changed, and not in ways that were predicted based on the aims and activities of the project. With no obvious other reasons why these practices and the network changed, I infer that the presence of the research team was a causative influence. These results challenge often-held assumptions about social impact and dissemination of agricultural practices by agroecological researchers and advocates. They provide insights into what type of agricultural innovations are more likely to be accepted among farmers, and, to some extent, how practices may most effectively be promoted within a community.

5.4.1 Changing farming practices

Over the course of the project, farmers changed their farming practices. More people started to use food waste, which corresponded to the banana peel composed treatment which was researched in the experimental gardens. People also took up behaviours that were not directly researched, such as mulching, and started to plant the specific variety of sweet potato that was used in the experimental gardens. These behaviours were especially popular among women. Applying animal manure and NPK fertiliser, on the other hand, were not widely taken up.

While the experiment was running, the research team did not know whether the tested fertilisers would indeed increase yields. Thus none of the fertilisers were actively promoted during this time. Despite this, some farmers created meaning from the researchers' presence in the community, similar to participants in the study described by Hakkarainen *et al.* (2019). This may in part be caused by the fact that some members of the research team were expatriates who were perceived as 'experts' with access to knowledge, which is regarded highly, especially in PNG (West, 2006). As it turns out, applying banana peel compost did not have a positive effect on sweet potato yields (Hazenbosch *et al.*, 2021), and I did not investigate the effect of mulching or the impact of the variety of sweet potato planted. So created meanings can be unexpected and have unintended effects on the community.

Created meanings may not only influence the society, but also the research itself. In the experimental gardens I planted the 'wan mun kaukau' sweet potato variety, following the advice of a local farmer. Only after the project had finished, did the farmer tell me that she had not been sure that the variety would grow well. However, she had thought that one of the contributions the research could make was establishing whether 'wan mun kaukau' would be a good variety to grow, something that the research team had not intended to investigate. It is not often that natural scientists reflect upon how their research 'subjects' may turn the tables on them, and influence researchers unintentionally to carry out research that they are interested in. Reflecting on this may allow agroecologists to develop a sharper sense of reality, and perhaps help tailor their research to answer questions that local people are interested in.

Looking at which behaviours were taken up provides insights into what type of agricultural innovations are likely to be accepted among farmers (Garnett *et al.*, 2009). Innovations that do not require fundamental changes in people's behaviour are usually much more readily accepted (Rogers, 2003). Mulching is traditionally practised in this community. Replacing grass, leaves or plant residue mulches with food waste was relatively easy, and this may explain why more farmers started to apply food waste (expanding the researched banana peels to include a range of other food waste products). Likewise, farmers in PNG already plant a great variety of crops (Bourke and Harwood, 2009), so switching the variety of sweet potato was also relatively easy. In a similar way, white yam (*Dioscorea rotundata*) was introduced to PNG in 1986 and has been steadily adopted by farmers, which is often explained by the fact that white yam has many similarities to the traditionally-grown greater yam (*Dioscorea alata*) (Risimeri, Gendua and Maima, 2001).

Applying animal manure and NPK fertiliser required new knowledge and inputs. Farmers indicated that despite the research intervention they did not think they had enough knowledge and practical experience yet to start using these fertilisers. They also thought it too difficult to acquire the necessary materials; collecting animal manure requires farmers to buy and fence animals and getting NPK fertiliser involves going to town, both of which demand time and money. Not having enough knowledge and initial costs are often barriers to innovation among farmers (Piñeiro *et al.*, 2020). Future research that aims to develop and promote agricultural techniques would benefit from harnessing existing practices and optimising them, rather than introducing completely new practices (Rogers, 2003).

5.4.2 Rewiring information-sharing networks in a smallholder farming community

I found that the research project, at least temporarily, affected the social network in the community. Local community members who were directly involved in the project as research assistants became more sought-after for advice. The intervention provided research assistants with external information, which may have helped them to increase their prominence. This phenomenon is not unique to PNG. Beaman *et al.* (2020) found that farmers in Malawi who had received training had on average more conversations than control farmers, and similarly Matous and Wang (2019) reported that farmers in Sumatra gained higher levels of influence in their communities after attending training events. In my project, however, project garden owners did not get nominated more often despite also being given information about the research and garden owners themselves indicating that they had learned from the project. However, they received little hands-on experience and played a less prominent role in the research project overall, which may have made them less attractive advisors.

My results demonstrate the importance of being mindful about who gets involved in a project. The choice of who to involve has implications for who will benefit, as also argued by Beaman and Dillon (2018). Researchers and advocates often collaborate with local leaders or elites as they are seen as gatekeepers to the resources needed to successfully complete the project (Toomey, 2016). This can be appropriate, but there may be a risk of reinforcing existing social structures and further marginalising people on the periphery (Beaman and Dillon, 2018; Matous and Wang, 2019), which could ultimately lead to tensions within the community, and between external actors and local community members (West, 2006). Conversely, many donors require a focus on involving marginalised groups (e.g. women or youth). This too could lead to tensions through perceived threats to the established order. Project leads should thus think carefully about who gets involved, and aim to increase inclusivity in a culturally appropriate manner.

Examining the dynamics of social networks with respect to dissemination can also provide valuable information. Based on my findings it seems unlikely that relying on social networks to spread information and behaviours will always be successful in PNG. In Ohu, the learning network between farmers was decentralised and clustered based on geographical location and clan identity. People in PNG strongly identify with their clan, as clan membership allows people access to clan-owned land and gives people protection from external threats. Clan membership ties people to geographical locations, and limits movement as you need permission to access other people's land (Bourke and Harwood, 2009). This, combined with limited access to transportation facilities, may cause social ties to decrease when geographic distance between people increases, similar to findings from Ethiopia (Matous, Todo and Mojo, 2013). There is often competition for land-use rights and other resources among neighbouring clans, and even within a clan there may be competition amongst nuclear families (Baynes, Herbohn and Unsworth, 2017). Hence, people may be reluctant to share information, including information about farming practices or a research project, outside their close family. Therefore, it cannot be assumed that in PNG trained farmers will influence others. Instead, agroecological extension officers would benefit from identifying and targeting connected clusters of individuals at the start of an intervention, as this has been shown to be a highly effective strategy for diffusing behaviours (Centola, 2018). If resources are not sufficient to collect social network data to identify clusters, investing in reaching out to more farmers individually could be the next best strategy (de Lange, Milner-Gulland and Keane, 2021).

5.5 Conclusion

I show that agroecological research can actively shape individuals' behaviours and a community's social network. Agroecological researchers therefore need to move away from the idea that they are neutral parties shielded by the objectivity of science (Brittain *et al.*, 2020). Instead, researchers should envision impact as an ongoing emergent property throughout their project (Toomey, Knight and Barlow, 2017). Agroecological advocates, on the other hand, require a solid understanding of how social networks spread the desired information and farming practices so that they can use them effectively; in my case, information did not spread much beyond targeted farmers. Care should also be taken, by both agroecological researchers and advocates, about who to involve in a project, because this has consequences for who gains. Although these lessons may be well understood by some, there are few detailed empirical case studies that demonstrate them. Overall, my case study illustrates the need for agroecological researchers and advocates to think carefully about whether their assumptions are valid about how, when, and what parts of, their activities will translate into practice. This can help them to work more effectively towards their goal of solving challenges in agricultural production.

- Chapter 6 -

The times are changing: understanding past, current and future resource use in rural Papua New Guinea using participatory photography

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People taking photographs of their resources in Ohu, Papua New Guinea.

'We don't see things as they are, we see them as we are.'

- Anaïs Nin

Abstract

1. There is increasing recognition that local people's voices need to be included in research and planning processes to better understand what they see as opportunities and challenges for their future. This is necessary because of the intrinsic importance of public participation, and because it can help produce more appropriate and sustainable adaptation plans.
2. I apply participatory photography in a Papua New Guinean smallholder farming community to explore local perspectives on resource management, drivers of change and adaptive strategies.
3. Twenty-four farmers of different clans, genders and ages took photographs of items important to their livelihoods, focusing separately on the past, present and future. I discussed the photographs and their meanings in individual and group interviews, encouraging farmers to lead the conversations.
4. Results show that farmers are shifting from relying mainly on natural capitals to using financial, social and physical capitals, and that this causes changes in people's well-being. Villagers highlighted cash crop diseases, land shortages and lack of training as their main challenges. So far, people have adapted to changes by shifting to crop species that still yield well, and setting up small businesses and projects to have additional sources of income. Farmers saw education as key to their future as it would allow for better land management and diversification of livelihoods.
5. The participatory photography process provided triangulation of scientific studies, gave insights into farmers' perceptions, and highlighted adaptive strategies and the complexities of realising them. Overall, the results can be used in future research and planning processes in PNG.

6.1 Introduction

People are inextricably linked to their environment through their dependence on resources and ecosystem services (Millennium Ecosystem Assessment, 2005). Especially in rural and low-income areas of the world, people rely heavily on natural resources for their livelihoods and well-being (Fisher *et al.*, 2014). A growing body of conceptual frameworks and empirical research (e.g. TEEB (2010), Díaz *et al.* (2015), Fisher *et al.* (2014), Summers *et al.* (2012), Cruz-Garcia *et al.* (2017)) shows how ecosystem services, such as soil formation, food, water purification and spiritual fulfilment, contribute to human physical, physiological and psychological well-being (King, Renó and Novo, 2014).

Increasingly, many rural and low-income communities are impacted by social and ecological changes (Bennett, Kadfak and Dearden, 2016; Masterson, Mahajan and Tengö, 2018). These include, for example, growing populations, shifts to new livelihoods, climate change, external actors moving into their area, changes in regulatory frameworks and the transformation of local ecological knowledge. Communities need to respond to these changes, and the extent to which they are able to do this has implications for both well-being and environmental sustainability (Bennett and Dearden, 2013).

There is an increasing recognition of the need to engage local and indigenous groups on their own terms, and have them fully participate in research and planning processes aimed at supporting their communities to address rapid and ongoing social-ecological changes (Mistry and Berardi, 2016; Heiner *et al.*, 2019). This is necessary because of the intrinsic importance of public participation, and because it can help produce assessments and adaptation plans that are appropriate and sustainable (Bennett, Kadfak and Dearden, 2016). Specifically, local perspectives can help triangulate and expand scientific knowledge (Bennett and Dearden, 2013). Insights from indigenous knowledge and perspectives in regard to ecosystem management are also of interest, as indigenous groups have resource-use practices that are tailored to work in complex ecological systems (Berkes and Berkes, 2009; Heiner *et al.*, 2019), and local communities tend to look for holistic solutions to emerging issues (Mistry and Berardi, 2016). Additionally, involving local actors makes research and planning processes more acceptable to the societies that they seek to support, while promoting social justice (Pascoe, Dressler and Minnegal, 2019) and establishing self-determination as a key principle of engagement (Mistry and Berardi, 2016). Local perspectives may be diverse as communities are not homogenous, however (Klein *et al.*, 2014). It is thus important to engage with a range of local actors to capture as many voices as possible. Participatory methods have been developed to incorporate community knowledge, preferences and values into research and planning processes (Masterson, Mahajan and Tengö, 2018).

One participatory method that has been successful in actively involving participants, highlighting multiple perspectives, promoting dialogue, and informing policy, is participatory photography (Wang and Burris, 1997). In participatory photography people photograph their everyday lives, and the photographs are subsequently used to identify people's perspectives and challenges, catalysing conversations and encouraging action. Participatory photography has been successfully applied, especially within anthropology, sociology and cultural studies (Harper, 2002), and public health (Catalani and Minkler, 2010). In the literature it has taken various forms, such as photo elicitation, autodriven photo elicitation, photo-elicitation interviews, photo novella, photo interviewing and reflexive photography or autodriving (Gotschi, Delve and Freyer, 2009). The different forms of participatory photography differ in their goal of either informing research (such as photo elicitation) or promoting social action (such as photovoice). What binds the different concepts together is that the active role of participants is emphasized in the generation and interpretation of photographs (Gotschi, Delve and Freyer, 2009).

Increasingly, participatory photography is used in resource management research and planning. The method has been applied, for example, to examine the links between the environment and human well-being (Masterson, Mahajan and Tengö, 2018), the social and ecological changes that are affecting these relationships (Baldwin and Chandler, 2010; Bennett and Dearden, 2013), and how communities are responding (Bennett and Dearden, 2013). Benefits of using participatory photography in this field are that the visual form of communication inherent to participatory photography allows those things to be captured which may evade textual description, and thus can lead to richer data compared with exclusively verbal methods (Pain, 2012). It helps overcome researchers' preconceived notions, and generates local, comprehensive and more emotional perspectives on nature's intrinsic and cultural values which are otherwise hard to obtain (Masterson, Mahajan and Tengö, 2018). Participatory photography also allows participants to become researchers and advocates for their own circumstances and to take ownership of the project, thereby opening up spaces for self-driven discussions of the future (Jenkins and Boudewijn, 2020).

I apply participatory photography in a smallholder farming community in Papua New Guinea (PNG) to explore local perspectives on resource management, drivers of change in resource use and availability, along with their responses to those changes. Currently, rapid social and ecological changes are taking place in PNG, which include ecosystem changes, population growth and shifts to new livelihoods (Bourke and Harwood, 2009). PNG's government has developed a long-term vision, *Vision 2050*, which hopes to address these changes (National Strategic Plan Taskforce, 2011). If *Vision 2050* is to be successfully implemented it will need to engage local actors, as PNG is one of the few countries where customary ownership of land and its resources is recognised under the nation's Constitution, and 97% of the land is under customary land tenure (Anderson, 2010). Photographs can serve as a starting point for discussions about resource management and social-ecological changes by farmers in PNG. By giving voice to local people's perspectives, this research contributes to better understanding of resource management, social-ecological changes and adaptive capacities in farming communities in PNG.

6.2 Materials and Methods

6.2.1 *Context*

The project was conducted in Ohu (S 05°13.081', E 145°40.735'), a village located 12 km west from the town of Madang in PNG. Ohu has a long standing collaboration with The New Guinea Binatang Research Centre (NGBRC), a local non-profit organisation committed to conducting biological research and conservation in PNG (Weiblen and Moe, 2016). The research team, which consisted of Papua New Guinean and international researchers, had been conducting social-ecological research in Ohu for two years before embarking on the photography project, and had thus built up relationships of trust with the participants.

The social-ecological system in Ohu is representative of other landscapes in Madang province and Lowland PNG in general. The vast majority of people rely on swidden farming for their daily food and income. Farmers use clan-owned land for making their gardens, and grow a combination of food crops (such as banana and sweet potato) and cash crops (such as betel nut and cacao) (Hazenbosch *et al.*, 2021). The original mosaic of primary and secondary forest around the village has changed since the 1980s into a more intensively managed landscape with food gardens, young secondary forest on abandoned food gardens, family plantations and village settlements (Sam *et al.*, 2014).

Some of the remaining fragments of primary forest are being preserved as a village-based protected area, now called WIAD Conservation. WIAD stands for Watup, Inamus, Asial and Dougu, and refers to the customary lands which are being conserved. Preservation of this area started in the 1950s when people in Ohu became concerned about declines in different species of bird of paradise (family Paradisaeidae), whose feathers they used for traditional dresses, festive dances and customary gift exchanges. Four clans in Ohu came together to establish an agreement to set aside a part of their customary lands in which hunting, mining, logging and gardening were forbidden. Currently two of these clans are still actively involved in the management of the conservation area.

WIAD Conservation is currently one of the few remaining Lowland rainforests around the town of Madang. It hosts significant biodiversity including the king-bird-of-paradise (*Cicinnurus regius*), lesser bird of paradise (*Paradisaea minor*) and rare birdwing butterflies. New species are still being discovered at WIAD Conservation, and often named after the place and its people. For example, *Kradibia ohuensis* is a fig pollinator and is named after Ohu, and *Ficobracon brusi* is a parasitoid which is named after one of the co-authors of this chapter (Van Achterberg and Weiblen, 2000). In collaboration with NGBRC, Papua New Guinean and international researchers often visit Ohu and its conservation area to conduct ecological research, which brings some economic benefits to the village (Weiblen and Moe, 2016).

Ohu is currently undergoing rapid social-ecological changes, including increased connectivity to town, population growth and ecosystem changes, like many villages around Madang (a growing town of currently approximately 30,000 people). How these social-ecological changes affect the livelihoods of local farmers in Ohu has consequences for their well-being and for WIAD Conservation. It is thus of interest to both agricultural development organisations and conservationists to understand what changes are affecting Ohu, how people are responding to them, how local landowners see and plan the future, and how these challenges and adaptations relate to PNG's *Vision 2050*.

6.2.2 Survey

Participatory photography research usually consists of six steps: (1) recruitment of participants, (2) completion of a training workshop, (3) conduction of the photography assignment, (4) interviews based on the photographs, (5) analysis of the main topics and themes, and (6) creation of a public facing output (Samuels, 2004; Bennett and Dearden, 2013; Shaw, 2013). I followed these steps and tailored the exact content and format to the context of Ohu so that the project was ethically and culturally appropriate. Free prior informed consent was given orally by all participants before the start of the project. The protocol was approved by the University of Oxford's Research Ethics Committee under permit number R58337/RE004.

I asked local village leaders to help me recruit participants in order to respect cultural norms. With their assistance, I recruited 24 local people. Purposeful recruitment was necessary to attract a representative sample from the community (Wang and Burris, 1997). Participants came from three groups; the first and second groups were selected from the two clans that are still heavily involved in the management of WIAD Conservation, and the third was recruited from clans that are less involved in the conservation area (Appendix D, Table 1). Groups were kept separate as resources in PNG, including WIAD Conservation, are often contested and I wanted to avoid causing any intra-clan or intra-tribe tensions (Baynes, Herbohn and Unsworth, 2017). Within each group I asked both younger (< 40 years) and older (> 40 years) people, and men and women, to participate as relationships with resources in PNG can differ between these groups.

With respect to the second, third and fourth steps, I was aware that being known to be carrying a camera could put the participants at a higher risk of being robbed because cameras are seen as a valuable resource in PNG, similar to Jenkins and Boudewijn's (2020) experience when working with female anti-mining activists in Peru. I thus only asked participants to carry cameras during the day (they returned the cameras at night to the research team) and conducted the photography project over a short period (two weeks) at the end of the two-year research project to minimise risks to both participants and the research team.

I worked with each group over four days. On the first day, a training workshop was organised in which issues of ethics, health and safety, and participants' expectations of the project were addressed. I also taught participants how to use tablets and how to take photographs with them. I chose to use tablets rather than cameras, as tablets allow participants to immediately see their own photograph and decide whether they are happy with it. Everyone was given the opportunity to practice using the tablets until they felt comfortable with them. I took ample time for the training part of the project as for many of the participants this was the first time they handled a tablet.

On the second day, I proceeded to step three of the participatory photography process. I asked participants to use their tablets to take photographs of 'things on your land that are currently important for the lives of people in your clan'. I specifically encouraged participants to think about their clan rather than their individual lives so I could get a clan-wide understanding, from the perspective of different groups. I explicitly asked participants to photograph only their own clan resources to avoid creating tensions between clans. I also asked participants not to photograph any people as I could not guarantee that potentially photographed people would be able to give permission for their photograph to be taken. Participants could take a maximum of five photographs, to allow for the limited battery life of tablets, the amount of photography paper that I could transport, and the time the subsequent interview would take, as participants were busy with their daily lives. People were given as much time as they needed to take photographs. Upon their return from the photography assignment, I printed their photographs.

The research team then discussed the printed photographs one by one in in-depth, face-to-face, individual interviews. Interviews were open in format to allow participants to tell their own stories about their photographs. Interviews covered what was photographed, what role the item played in the life of the participant's clan, how the item had changed and may change over time, and what people were doing to adapt and respond to these changes. Interviews were conducted in Tok Pisin (a language commonly spoken in PNG and by all members of the research team involved in data collection) and recorded with the permission of participants. At the end of the interview, the research team specifically asked participants whether there was anything that they wanted to photograph but were unable to, and whether they had any questions about the project so far. The team also asked all participants if their photographs could be used for analyses and publication. It was made clear to participants that their data would only be used for scientific purposes, and would not be sold on to any other people or companies. The research team also highlighted its intention to bring back copies of the outputs to Ohu. I specifically allowed time for participants to question the team on these statements, as there are cases in which scientists have been suspected by local communities not to have shared the financial benefits of a research project fairly with them (West, 2006), and I wanted to avoid confusion or misunderstanding as much as possible. After the explanations and answering participants' questions, all participants gave their oral approval for the use of their photographs and interviews.

On the third day, the same protocol was repeated but this time I asked people to photograph 'things on your land that were important to the lives of people in your clan when you were a child'. It was made clear to participants that they were allowed to photograph the same item as the day before if they felt that the item still plays an important role. On the fourth day, the prompt was changed to 'things on your land that you think will be important to the lives of people in your clan when today's young children have grown up'. Again, participants were allowed to photograph similar items to previous days. Emphasizing the present on the second day, the past on the third day and the future on the fourth day, allowed me to explore past, present and future natural resource use and social-ecological changes in depth. I chose to encourage participants to think about time in terms of generations rather than specific years, as this is the timescale on which important changes are happening (Pascoe, Dressler and Minnegal, 2019) and the goals of *Vision 2050* will be realised.

On the final day, I organised focus groups to discuss the photographs in a group setting. I conducted the groups with men and women separately, because in Ohu the society has a patrilineal structure with men being seen as the decision-makers (Baynes, Herbohn and Unsworth, 2017), making it more difficult for women to speak out when men are present. During the focus group each participant got the opportunity, if they wanted, to present his or her most important photographs to the group. We then discussed as a group the most important changes that were being highlighted, adaptation measures that people have put, or are putting, in place and how the future of Ohu and its WIAD Conservation area looks like.

At the end of the data collection, interviewees received printed copies of their photographs. They were also given a small monetary payment to compensate for their time and effort, following NGBRC guidelines. Often a public-facing output is produced at the end of a participatory photography project with the intention of reaching a larger audience (Jenkins and Boudewijn, 2020). This was not done in this case, to avoid creating tensions between groups.

6.2.3 Thematic and statistical analyses

Data from participatory photography are rich, reflecting the multiple levels of analysis, including: (1) content of the photograph (i.e. what is represented in the photograph?), (2) the participant's interpretation of the photograph (i.e. what is the story behind the photograph?) and (3) assessment of differences by the researchers (i.e. is there a difference in photographs taken and their interpretations between different groups?) (Gotschi, Delve and Freyer, 2009). A hybrid approach that examines the different levels using theory-driven deductive techniques and data-informed inductive techniques is most likely to gain a holistic understanding of the data.

I used a deductive method to analyse the content of the photographs, meaning that I grounded myself in existing theoretical frameworks (Braun and Clarke, 2006). When describing the content of the photographs, participants often highlighted two aspects; first, what resource they had photographed, and second how the item contributed to their daily life. Resources can be conceptualised as natural, human, social, financial and physical capitals (Carney, 1998; Scoones, 1998) (Appendix D, Table 2). I classified each resource into one of these capital categories (Appendix D, Table 3). Some resources could be classified into multiple categories. For example, in PNG pigs are often used for economic transactions and could thus be marked as both natural and financial capital (Sillitoe, 1999). I based the final classification of a resource by looking at which definition matched the resource most closely. In the case of pigs, this would be natural capital, for example.

Next, I captured the multiple uses of a resource in day-to-day life. When describing how the item contributed to their daily life, participants highlighted the positive and negative contributions of the resource. These descriptions were classified using Narayan *et al.*'s (2000) framework of well-being and ill-being. Based on research across 23 countries Narayan *et al.* (2000) identified that having sufficient material assets, health, social relations, security, and freedom of choice and action contributed to well-being. Dimensions of ill-being were often the opposites of well-being dimensions, with material lack, poor health, bad social relations, insecurity and powerlessness contributing to a 'bad life' (Appendix D, Table 4). For an overview of which descriptions were classified into which category of well-being or ill-being, see Appendix D, Table 5.

I used an inductive method to analyse the story behind each photo. In an inductive analysis, in contrast to a deductive one, codes are created after carefully reading the text and identifying which themes and patterns emerge, allowing for novel and unexpected themes to arise (Braun and Clarke, 2006). In this case, the story of the photograph was about how the photographed resource had changed and is changing, what causes these shifts and how people have adapted or are responding. Since these stories are highly localised it would have been inappropriate to use an existing framework. I listened to the interviews multiple times and noted down the main changes, drivers of change, and adaptations that people were mentioning. I then created corresponding codes, which allowed me to group the descriptions. For example, the quote 'Land will be short because of population growth. Some people will go to school and get a job so that they can earn money' was coded as 'the land is becoming short' (describing a change that is happening in Ohu), 'the population is increasing' (describing a driver of the change) and 'education is becoming more important' (describing an adaptation strategy). For a full list of codes that emerged, see Appendix D, Table 6.

I used statistical analyses to assess differences between time periods (past, present and future) and social groups (younger vs. older people, and men vs. women). To assess whether capital and well/ill-being components had changed from the past to the present, I conducted Fisher's exact tests on the discrete quantities within the different categories of capital and well/ill-being. If there was a significant overall change, I used row-wise post-hoc tests with a Bonferroni correction to identify which capital or well/ill-being component had changed significantly. I repeated this procedure to determine changes from now to the future. To assess differences between groups I first split the data by time category. I then conducted Fisher's exact tests and post-hoc tests for younger vs. older people and women vs. men for each time category separately. All statistical analyses were done in R version 4.0 (R Core Team, 2020). To conduct the Fisher's exact test and the post-hoc test I used the functions 'fisher_test' and 'row_wise_fisher_test' from the rstatix package (Kassambara, 2020).

Results from the focus groups discussions were analysed by carefully reading the transcripts of the interviews and drawing out the main themes.

6.3 Results

A total of 360 photographs were taken. None of the interviewees indicated that they did not photograph what they wanted to.

6.3.1 Capitals and well/ill-being

Out of the five capitals, natural capital was photographed most often, followed by physical capital, and then social and financial capital. The prominence of different types of capitals changed significantly depending on the time period people were asked to think about (Table 6.1, and Appendix D, Table 7), but there were no significant differences between demographic groups (younger vs. older, and men vs. women) in the capitals that they highlighted (Appendix D, Table 8). Of the different components of well- and ill-being, 'basic materials for a good life' was mentioned most frequently, followed by 'freedom of choice and action' and 'good social relations'. Similar to capitals, the prominence of the different components of well- and ill-being changed significantly over time (Appendix D, Table 7), but there were again no significant differences between demographic groups for any of the individual components of well- and ill-being (Appendix D, Table 8).

Table 6.1 | Capitals photographed by participants which they thought were important when they were young (left), are important now (middle) and will be important for their children (right). Note that human capitals were not photographed because I specifically asked participants not to photograph people. n = 360 photographs.

Capital	Past	Present	Future	Total
Natural	94	109	40	243
Human	0	0	0	0
Social	2	1	19	22
Physical	24	7	42	73
Financial	0	3	19	22

In the past natural capital provided people with the basic materials to live a good life (Fig. 6.1). For food, families relied on crops in their gardens such as bananas and coconut, and plants in the forest such as tulip and sago (Fig. 6.2A). People also used coconut and sago, together with bamboo, to build houses. To earn money, individuals would mainly sell crops including banana, coconut, sago and tulip. Since access to health care services was limited, people relied on their natural resources for traditional medicines. For example, banana and papaya were used to relieve pain and sickness. However, some plants such as bamboo also caused harm by cutting people, and in that way contributed to ill-being. Lastly, natural capital played an important role in maintaining good social relations. In particular, pigs, bananas, coconut and tulip played a crucial role as important contributions to weddings and funerals (Fig. 6.2A). Pigs, however, could also cause trouble by disturbing people's gardens. Physical capital such as pig teeth and grass skirts was also important for customary practices such as 'singsings' (traditional dances). Tools aided families in their work, although they, like bamboo, also contributed to poor health as tools could cut you if not handled properly (Fig. 6.2A).

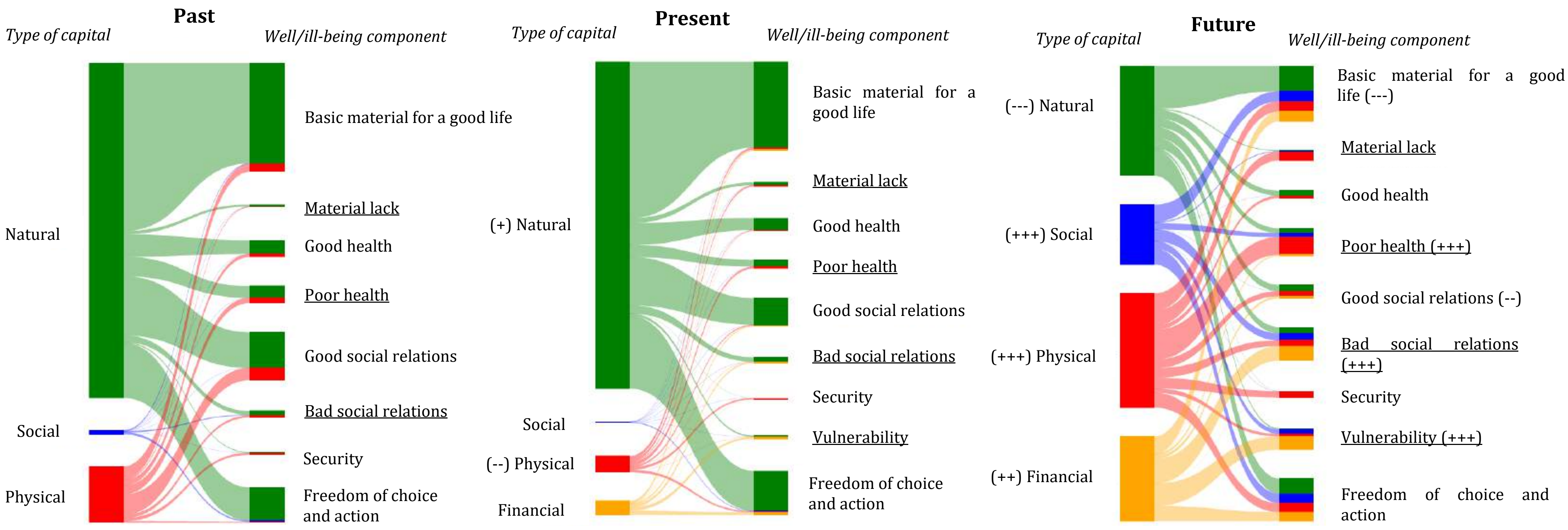


Figure 6.1 | Type of capital and their contributions to the different component of well- and ill-being as highlighted by interviewees in the past (left), present (middle) and future (right). The types of capital that were that were highlighted in the interviews included natural, social, physical and financial capital. Well-being components included 'basic material for a good life', 'good health', 'good social relations', 'security' and 'freedom of choice and action' and are not underlined, whereas the ill-being component included 'material lack', 'poor health', 'bad social relations' and 'vulnerability' and are underlined. Overall counts of capitals and well/ill-being components determine the width of a bar. Model results of the row-wise post-hoc test with a Bonferroni correction are included with + indicating a significant increase and - a significant decrease in the count of the specified capital or well/ill-being component between time-periods. +/- = p < 0.05, ++/-- = p < 0.01, +++/--- = p < 0.001. For full results, see Appendix D, Table 7 and 8. This figure was created using the R package 'bipartiteD3' (Terry, 2019).

At the moment, people still rely heavily on natural capital in their daily lives (Fig. 6.1). Land was often photographed, with many participants remarking that land is the basis for their lives (Fig. 6.2B). Bananas, coconut, sago and tulip are still widely consumed. A crop that has gained prominence for food is Chinese taro (Fig. 6.2B), which was introduced to PNG after 1870 (Bourke and Harwood, 2009). Chinese taro is now also used in customary practices. Pigs, however, are less often kept and used for customary purposes compared to the past, as Ohu community has introduced rules to limit the risk of pigs disturbing farms, consequently making pig rearing more cumbersome. People still rely on coconut and sago to build their houses. However, this is becoming more difficult as many coconut trees are now sick and the number of sago plants is declining because people still harvest sago but plant it less often. Coconut and banana are still being sold, but unlike in the past individuals now also sell betel nut and cacao (Fig. 6.2B). Betel nut is also consumed by local people themselves as a recreational stimulant, and it is customary to exchange betel nut with friends and family. Compared to the past, families invest more time and effort in growing and selling cash crops. With respect to physical capital, participants no longer highlighted tools and traditional items, indicating that these items play a smaller role nowadays. Instead, interviewees said that their house, cars, cacao fermentary and modern (cotton) clothes are important. Financial capital also made its entrance when discussing the present, with a few people highlighting that money is an important resource nowadays.

In the future participants expected natural capital such as land and water to still be important, but less so than before. Interviewees expected clans to move away from relying on natural capital for their food and finding shelter. Instead, they will use money to buy food such as rice, vegetables and canned fish, and building materials for their houses such as corrugated roofing (Fig. 6.2C). Store-bought foods are easy to cook, participants remarked, although they also said that these foods are not healthy and that its packaging can spoil the environment if people do not dispose waste properly. People are excited to start living in modern houses as they last for a long time, although it was remarked that corrugated roofing can make the house feel hot and hurt you if a house collapses. Interviewees also highlighted that money may be used to buy alcohol and weapons, which could lead to more fights and divorces, worsening social relations. To earn money, participants expected people to have to go to school to gain the necessary knowledge to get a job or set up a business, such as running a small store or selling poultry (Fig. 6.2C). Some interviewees pointed out that if individuals fail to get money they may revert to stealing or prostitution, which would lead to more community problems and increase people's vulnerability. Participants expected the next generation to be less concerned with maintaining past and present customs. If exchanges still happen, interviewees thought that money and store-bought foods will be used rather than homegrown foods. On the other hand, modern tools such as mobile phones may help people to stay connected and improve social relations.

Banana – Participant 3

'We used to sell bananas and earn money. We would eat bananas. And we would use them for customary purposes. If someone had died we would get bananas and bring it to the funeral. Or we would give bananas to our friends.'

Pig – Participant 24

'Before, we used to eat pigs and we used them for customary purposes. We would also sell them. Or if people didn't want to eat the pig themselves they would trade it with other people.'

Axe – Participant 11

'When the axe worked, we could eat. We used it to make our garden and to plant crops which then provided us with food.'

B

<u>Land – Participant 19</u>

‘Land is useful for building a house, for growing food, for planting fruits and for many other things.’

<u>Chinese taro – Participant 13</u>

‘When I was young Chinese taro wasn’t popular. Taro, yes, taro was popular. Now taro is starting to disappear and Chinese taro is becoming popular and is taking over taro’s work.’

<u>Betel nut – Participant 19</u>

‘Now many people plant betel nut. Before only few people planted betel nut. People thought that it was a useless tree. But now we earn money with betel nut.’

<u>Modern house – Participant 12</u>

'Now we use materials from the forest to build our house. In the future these materials, including sago leaves, will no longer be available and we will depend on corrugated roofing to build our house.'

<u>Money – Participant 7</u>

'In the future people will not build their house, people will not make food gardens. Money will buy a house, money will buy food. People will depend on money.'

<u>Shop – Participant 23</u>

'I think that in the future people who can't find a job will run an informal business so they can sustain their livelihoods. It will allow them to earn money.'

Figure 6.2 | Photographs and accompanying quotes portraying capitals in the past (A), present (B) and future (C).

6.3.2 Changes, their drivers and adaptations

Life in Ohu has changed and is still changing due to the influence of different drivers. Participants were noticing that, compared to the past, many of their crops and animals have become sicker in the last couple of years. Traditionally important crops such as bananas and coconuts are now displaying symptoms with their leaves turning yellow and withering, and cacao is also not doing well (Fig. 6.3A). Some interviewees thought that crops get sick because insects attack them.

Others linked it to changes in the weather. Related to this, many people complained that the yields from their gardens are declining; in particular banana and taro no longer grow well. Part of this is felt to be a direct result of the increase in crop diseases, but many also remarked that it is a result of declines in soil fertility. Participants said that they now only have small areas of land to work because of an increase in the number of people living in Ohu. This is forcing them to use their land and soils more intensively, causing yields to decline (Fig. 6.3A). Land shortages are also causing more disputes between different families about who owns what land, and who can make use of it. The increase in population and in the number of gardens and cash crop blocks has caused a lot of forest to be cut (Fig. 6.3A). The loss in big trees is, in turn, negatively affecting water flows in Ohu, according to interviewees, with streams being smaller, less cold and tasting sour nowadays.

To deal with the changing situation, farmers have started to plant different crop species. For example, farmers now often grow Chinese taro instead of taro, and betel nut instead of coconut and cacao. However, betel nut is now also sometimes getting sick and displaying similar symptoms to banana plants and coconut palms. This is causing some farmers to shift again, and they are starting to grow vanilla (Fig. 6.3B). Peoples also continue to shift away from relying on natural resources. For example, instead of using tulip trees to make traditional bags called 'bilums', women use string and wool, and people are starting to buy food from supermarkets (Fig. 6.3B). Families are also becoming more concerned with sending their children to school, so they have alternative ways of making a living (Fig. 6.3B). Participants frequently mentioned that it can be challenging to pay for the school fees, especially when children continue to secondary and tertiary education. When discussing this in the focus groups, participants often highlighted the importance of working together as a family and a clan to find the necessary money and resources to support a child's education.

A

Cacao fermentary – Participant 18

‘Climate change came and is destroying cacao. All my pods are now spoiled. Now we are all no longer cleaning our cacao trees. We stopped doing that now. The pipe of the cacao fermentary also broke.’

Sweet potato – Participant 14

‘When I was young, we had enough land and the soil was rich. So we used to harvest quite big crops. But now we keep using the same land for our garden. You can’t move because other family members will be there because the population is growing. So now crops like sweet potato are small.’

Forest – Participant 7

‘We cut the big forest just to make gardens. Now all the birds, cassowaries and wallabies have disappeared. Maybe the fire killed them all.’

B

Vanilla – Participant 12

'Now we are starting to plant vanilla.'

Bilum – Participant 19

'Before people used bilums made from tulip. But nowadays we make bilums from string.'

School – Participant 23

'In the past many people didn't understand the importance of education and they didn't send their children to school. The school was there, though. But now many of us are realising how important education is and we bring our children to school.'

Figure 6.3 | Photographs and accompanying quotes portraying how life changed from the past to the present (A), and how local community members have adapted to the changes so far (B).

Going forward, people anticipated that natural resources, including betel nut, tulip, banana, coconut, pigs, sago, Chinese taro and water, will still be available. However, they did expect many of them, including coconut, sago and banana, to decrease in abundance as a result of disease in the case of coconut and banana, and over-harvesting of sago. Participants also expected the population to continue to grow, which will result in land becoming even scarcer. Some are predicting that Ohu will further develop, and that in the future the village will host a big modern aid post, will be connected to power and dam the water (Fig. 6.4A). A few interviewees were wondering whether mining companies will show interest in their land and resources. Some expected potential mining projects to yield money and help develop the area by building schools and hospitals, but it was also said that mining would destroy their land, water and resources.

Some participants pointed out that the decrease in natural resources may encourage people to start conserving them. People in Ohu have already made a start with this by setting up their locally owned WIAD Conservation project, and many participants are keen for this project to continue (Fig. 6.4B). Nevertheless, interviewees are foreseeing shortages in natural resources and thus they are pushing their children to go to school. They hope that by going to school, children can gain the necessary knowledge to either look after their land well and keep selling cash crops, or to find a job and get paid a wage (Fig. 6.4B). Earning money will allow them to shift away from relying on food gardens and forests, and instead they can buy food in the supermarket and materials in the store. When discussing the future and education in the focus groups, participants pointed out that it will be necessary for them to build their own schools rather than to 'wait for the government'. They also highlighted that it is important that clan members who manage to get an education return to the community to help teach the next generation. Participants expected the changes in livelihoods to cause people to become more independent and less concerned with maintaining traditional customary knowledge and relationships (Fig. 6.4B).

A

Land – Participant 23

‘We use land to make gardens, to build houses and to plant cash crops. I think that the next generation will not plant anything. Instead they will use the land to build buildings and development will come.’

Aid post – Participant 14

‘In the future when there is no more land because of development and the population is big, it will be difficult to find any bush medicines, so we will need to get medicines from the aid post.’

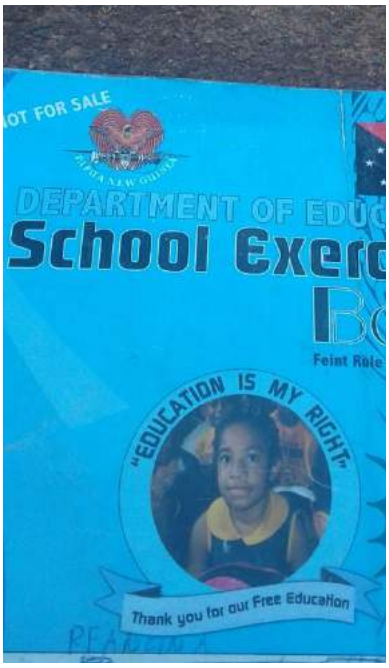
Generator – Participant 12

‘Now we use small torches to get light. I don’t think this will be the case in the future. Modern technology is reaching us now. We will start using electricity soon.’

B

Conservation – Participant 8

‘When we brothers hold each other’s hands things will change for the conservation area. We will no longer destroy the trees. The conservation area will expand. All trees will grow again. The forest will thrive.’



School – Participant 15 [1]

‘Now our lives depend on our gardens. But in the future there will be no more gardens, because the population will increase. Our children will need to go to school and they will depend on their knowledge for their survival. School will be to them what gardens are to us today.’

Store food – Participant 7

‘Now we use rice and canned fish for our customs. We buy a bag of rice or a bale of rice, and we buy half a carton or a full carton of canned fish and we will use it for making custom. But this will change again, because now many are feeling that it is too expensive to make custom.’

Figure 6.4 | Photographs and accompanying quotes portraying how life is likely to change within the lifetime of the next generation (A) and how local community members think their children will adapt to current social-ecological changes (B).

[1] The photo was taken by a different participant (participant 8). The photo participant 15 took included school children. To protect their anonymity, I replaced that photo with this one. Both photos represent the item ‘school’.

6.3.3 A diversity or unity of views?

Within a community, perspectives may differ or converge. It is important to explore how widespread and (un)contested views are, as this produces a better understanding of what may work for which groups. During the focus group discussions, I found that for the most part people agreed with each other's analyses. Also between focus groups there was consistency in how people viewed the future. All groups marked land, food gardens and cash crops as their most important resources, population growth as the main driver of change affecting their resources, and education as key to their children's future. However, there were two important points on which groups differed. Firstly, the four focus groups containing participants closely involved in the management of WIAD Conservation highlighted that WIAD Conservation plays an important role in community development by bringing in education, cash and resources. The two focus groups whose participants were not directly involved in WIAD Conservation still saw it as an important asset, but argued that the community also needed additional projects such as a livestock-rearing project. The other contested point between and within focus groups was about the role that companies, including mining companies, would play in the future. Some predicted that companies will show interest in Ohu's resources and try to establish a project within the community. This would bring benefits, according to respondents, such as easy access to cash, but would also have negative consequences as land may be destroyed and water polluted. Others did not think so much about external companies and highlighted the importance of cash cropping and small business projects going forward.

6.4 Discussion

The participatory photography process yielded rich visual data and stories, which explored local perspectives on natural resources, social-ecological changes and adaptation strategies.

6.4.1 *Insights from using participatory photography in Ohu*

Results from the participatory photography project triangulated and expanded current scientific knowledge on social-ecological changes that are happening in PNG. Previous research on environmental change by Gurr *et al.* (2016) describes the increasing presence in PNG of Bogia coconut syndrome and banana wilt associated with phytoplasma, which causes coconut palms, banana plants, betel nut palms and taro to become diseased. Based on their photographs, participants also highlighted that many of their crops, and especially coconut and banana, are dying due to disease. Similarly, Fujinuma *et al.* (2018) describe how land use intensification is causing declines in soil fertility, Shearman *et al.* (2009) call attention to the negative impacts of smallholder farming on forest cover in PNG, Schmidt, Mueller and Rosenbach (2020) outline how people's diets change when they engage in off-farm work, and the World Bank (2020a) shows the rapid increase in PNG's population, all of which are also highlighted by the participants. In their stories participants also focused on the intricate interplay between all of the changes that are happening and their ultimate drivers. For example, when discussing crops, participants often went on to say that they attributed the increase in crop diseases to more frequent insect attacks and changes in the weather. These changes were, in turn, connected to the loss of local forest, which people attributed to a rapidly growing population, because more people needed to cut trees to make food gardens. Similarly, people related the decreases in soil fertility to land shortages, which again they attributed to a growing population. Ultimately, participants highlighted population growth as the main driver of change in their community.

People attributed most of the changes that they were observing to things that were happening in their own community, rather than placing the attribution for these drivers with external actors. This is similar to Pascoe *et al.*'s (2019) description of discussions of the causes of climate change with communities in Milne Bay Province of PNG. This focus on local drivers of negative environmental changes may reflect deeper conceptualisations of the relationship between people and the environment, and the scale at which change is generated and felt in PNG.

It also differs from the conceptualisation of causality that external actors (such as researchers) may have. Understanding local perspectives on the importance and interconnectedness of changes and their drivers enriches scientific knowledge. It is vital for better understanding which changes and drivers community members perceive as most significant and feel they have agency over, and may thus be keen to address (Bennett and Dearden, 2013).

The photography project also helped to shine light on the perceived consequences, both positive and negative, of social-ecological changes. Due to an increase in crop diseases, a decrease in soil fertility and forest loss, people are expecting to have to shift from relying mainly on natural capital to relying on a combination of natural, physical, social and financial capitals. If people succeed, participants pointed out that this may allow their children to increase their living standards. For example, they will have the necessary money to buy the materials to build a high-quality house. However, interviewees also said that moving away from natural capital may worsen social relationships if people use money to buy alcohol and weapons, and may increase people's vulnerability to stealing or prostitution. Identifying both vulnerabilities and opportunities, and acknowledging uncertainties is crucial when designing adaptation plans, as this may help in recognising and mitigating unintended consequences and allow positive opportunities to be nurtured (Masterson, Mahajan and Tengö, 2018).

Participants sought holistic adaptation strategies. For example, when people noticed a decrease in the abundance of birds of paradise, they linked this to a decrease in forest. They subsequently decided to preserve the remaining primary forest, which formed the basis for WIAD Conservation. Going forward, people expected other resources (such as sago) to further decrease, and they again highlighted the importance of conservation. How exactly to achieve conservation of resources while also accommodating a larger population may be difficult. One solution people in Ohu offered was to increase educational opportunities, which would allow them to kill two birds with one stone: it would help them to better manage their land as well as increase their chances of finding employment, earning money and buying items, allowing them to rely less on their direct environment.

However, implementing adaptation strategies can be difficult, and in certain cases this can cause communities to make complex decisions. For example, there is currently one elementary school and one primary school in Ohu where students can complete grade 1 to 8, while for secondary schooling students need to go further afield and either travel extensively on a daily basis or attend a boarding school. Theoretically, until 2019 schooling up to grade 10 was cost-free, as the government subsidised students' tuition fees (Department of Education, 2012), although often families still had to pay 'project fees'. In December 2019, the PNG government replaced their Tuition Fee Free policy with a Government Tuition Fee Subsidy, which involves families paying 37% of tuition fees (Ministry of Education, 2019). So in practice attending school in PNG has not been cost-free, and families often struggle to pay, as also highlighted by the participants. So far, people are relying on their cash crops to pay for school fees, and participants pointed to the importance of good cash crop management going forward. However, organisations or companies which offer to provide education or other development services are often warmly welcomed (Novotny, 2010; Soukup, 2012). At the time of research, there were ongoing debates within Ohu about whether a mining company should be allowed to enter the village. These discussions are not new, though, as already in the early 1990s a gold mining company had approached Ohu and undertaken scoping work. Eventually the mining did not go ahead as people feared that mining may destroy their land and pollute their water, resources that they currently rely heavily on. However, some are attracted by the idea of mining allowing them fast access to cash. These results show that people in Ohu, like many other communities, sometimes feel that they need to make trade-offs between conserving their land and forest, and realising community development (Jacobs *et al.*, 2020).

Interventions that seek to overcome the apparent tension between conservation of resources and people's priorities for development, such as access to education in Ohu's case, would be beneficial. Some clans in Ohu have made a start with this themselves by no longer using WIAD Conservation only to preserve the bird of paradise, but also as a means to attract (international) researchers to conduct fieldwork, bringing economic benefits, employment possibilities and educational opportunities (Weiblen and Moe, 2016). Other examples of initiatives that aim to bridge conservation with community development across PNG include a royalty payment scheme for the conservation of 10,000 ha of forest in Wanang (Novotny, 2010), the SURFACES project which works to integrate biodiversity conservation with improved access to health care (Middleton, Cassell, *et al.*, 2020), and the offering of a premium price for coffee grown by landowners of the YUS Conservation Area (Beehler and Kirkman, 2013). However, these programmes are not without challenges; for example sometimes local actors perceive the benefits as not sufficient or raise concerns about how the benefits are shared among different stakeholders (West, 2006; Soukup, 2012; Henning, 2015).

The findings of this work have implications for future research and government planning in PNG. Currently, PNG's *Vision 2050* acknowledges that agricultural research is important for the country's development, but does not mention specific areas of interest. Crop disease and land shortages were highlighted by participants as two key issues affecting current and future livelihoods. I recommend that research and government institutions focus part of their work around these two themes. Further implementation of projects that aim to bridge conservation with community development, and evaluation to learn lessons and support scale-up, would also be beneficial (Novotny, 2010; Benson, 2012; Beehler and Kirkman, 2013; Henning, 2015; West and Kale, 2015). Finally, participants highlighted the importance of their clans and tribes working together so they can realise the desired development, such as building a school, setting up a livestock-rearing project or improving the conservation area, without having to rely on outside organisations. However, currently families, clans and tribes are often divided (Baynes, Herbohn and Unsworth, 2017). *Vision 2050* acknowledges this and highlights the importance of resolving law-and-order issues around the country (National Strategic Plan Taskforce, 2011). However, participants believed that it is important to go beyond quelling tensions to also build trust within and between groups. Certain programmes, such as the Family Farm Team programme (Pamphilon, 2019), are already exploring how groups of people in PNG can be brought together to work effectively, and further exploration of this approach would be of great value.

6.4.2 The participatory photography method

The participants in this project overall expressed their enjoyment of the process of taking photographs and stated that it allowed them to select which aspects of their lives were most important to their clans, similar to Masterson *et al.*'s (2018) findings. People expressed their hopes and fears during the project, demonstrating that participatory photography can be a useful method to understand both positive and negative consequences of changes, as also highlighted by Bennett and Daerden (2013). Finally, the method encouraged community dialogue about the future as it brought families together, provided a space for both men and women to talk about the future, and caused people to highlight the importance of teamwork within their clan. This shows that participatory photography can stimulate self-determination and benefit the community beyond just the production of knowledge, as also argued by Jenkins and Boudewijn (2020).

Despite the many insights that the participatory photography process engendered, I did encounter some methodological limitations which future research could aim to improve. First, participatory photography relies on items having to be photographed at a given point in time, which may have limited people's ability to communicate their experience of the past and their vision for the future (Lopez, Wickson and Hausner, 2018). To overcome this, future research could combine participatory photography with additional arts-based methods such as drawing or embroidery which allow for less reliance on currently-present items (Soukup, 2012; Lopez, Wickson and Hausner, 2018). Second, I explicitly asked participants not to photograph any people as I could not guarantee that people in the photograph would have given permission for the photograph to be taken. This meant that I did not capture human capital. Since my main area of interest was natural resources, I do not believe this negatively affected the results in my study. However, if it would be of interest to include human capital, multi-year studies would allow the time needed to properly request permissions to be photographed.

6.5 Conclusion

Using participatory photography, I explored local perspectives on natural resources, social-ecological changes and adaptation strategies. The results provided an important triangulation for scientific studies and allowed the exploration of how different social and ecological changes interact. The process gave insights into participants' perceptions of the causes and consequences of these changes, highlighted adaptive strategies and the complexities of realising them, and provided suggestions for future research and planning processes. The photographs told the story of how farmers in Ohu have made, and are still making, complex decisions about how to manage their resources and achieve development of their community in the face of rapid social-ecological changes. As one of the participants put it: ‘We need to decide, if you have a banana and a coin in your mouth, which one do you want to swallow?’.

- Chapter 7 -

Synthesis

Brus Isua explaining future plans for forest conservation in Ohu, Papua New Guinea.

'A journey of a thousand miles starts from beneath one's feet.'

- Laozi

7.1 The changing world of swidden farmers

Swidden farming plays a crucial role in the food security and livelihoods of millions of people across tropical regions (Mertz, Leisz, *et al.*, 2009). However, as the results presented in this thesis show, swidden farmers are facing rapid and ongoing social-ecological changes to which they will need to respond.

7.1.1 Changes in the fields of swidden farmers

Farmers in Ohu are observing an increase in insect attacks on their crops, more crop diseases and a decrease in their soil quality (Chapter 4 and 6). They attribute this to deforestation and land use intensification, caused by a rapidly growing population within their community. This is not happening only in Ohu, but across Papua New Guinea (PNG). For example, pest and disease damage to crops and reduced soil quality are also increasingly becoming a problem in the Highlands of PNG (Gurr, Liu, *et al.*, 2016; Fujinuma *et al.*, 2018). In the years ahead, it is likely that further population growth, deforestation, land use intensification and climate change will take place across PNG, which will require a response from farmers.

7.1.2 Changes in the lives of swidden farmers

The socio-economic structures in which swidden farmers function are altering rapidly. Farmers in Ohu are increasingly focused on growing and selling cash crops, including betel nut and cacao (Chapter 6). This mirrors trends across PNG in which swidden farmers are increasingly becoming integrated into the market economy (Bourke and Harwood, 2009). As described by farmers in Chapter 6, this brings opportunities as money allows them to build better houses, pay for school fees and access medical services, but it also leads to problems such as an increase in fights and family issues.

In addition, increasingly farmers are approached by external actors and put under pressure to use their land for alternative purposes than swidden farming. Villagers in Ohu have been approached by conservationists who were hoping to set up a conservation and research area, but also by representatives from mining companies keen to start a mining project (Chapter 6). Other villages in PNG also have to deal with external pressures. For example, Wanang village was approached by a logging company but opted to collaborate with The New Guinea Binatang Research Centre (NGBRC) instead, accepting a royalty payment scheme for the conservation of their forest (Novotny, 2010). In the Crater Mountain area, however, a conservation-as-development project was abandoned, whereas an oil exploration and refinery company was allowed to continue its work (West and Kale, 2015). PNG has an abundance of natural resources, including high biodiversity, extensive areas of native forests, and large deposits of minerals, petroleum and natural gas (Laurance *et al.*, 2012), all of which are of interest to different actors. Swidden farmers in PNG are increasingly put in a position of choosing between different types of land uses, with far reaching consequences for their day-to-day lives and well-being.

7.1.3 A continuously changing world

Even since this research was conducted, new developments have taken place in PNG, affecting swidden farmers. In March 2020, PNG recorded its first case of coronavirus disease 2019 (COVID-19) (Gwara, 2020), and continues to be affected by the disease (The World Bank Group, 2020b). In the same month, the first case of African swine flu (ASF), a lethal disease of domestic pigs and Eurasian wild boars caused by a DNA virus (*Asfarviridae: Asfivirus*), was also reported (Penrith, 2020). Domestic and international trade have been negatively affected by COVID-19 and ASF, and policy regulations to reduce their spread have limited movement of people and goods across the country, making it more difficult for swidden farmers to sell their products (Robins *et al.*, 2020; Schmidt and Fang, 2020). Besides, a La Niña event affected PNG from August 2020 to May 2021 (World Meteorological Organization, 2021). In the past, La Niña has led to increased rainfall and more flooding and landslides in PNG, with a potential to cause damage to standing crops and trees (FAO, 2021a). The extent to which this happened, and how it has impacted swidden farming in PNG is yet to be confirmed. On a more positive note, vanilla from PNG is gaining increased acceptance in the industrial extract market, and may represent an opportunity for swidden farmers in PNG (Aust & Hachmann, 2020).

For many generations, swidden farmers have successfully navigated change; so much so that one could argue that change itself is inherent to swidden farming. However, changes are ongoing and farmers will need to continuously find ways to respond to sustain their food security and livelihoods. I will now discuss key interventions which can help swidden farmers to continue living well and working in an ever-changing world.

7.2 Increasing and intensifying yields

One of the main challenges that swidden farmers face is feeding a growing human population (The World Bank Group, 2019b). There is often limited land available for expansion, either because the remaining landmass is unsuitable for agricultural production, has a high conservation value, or swidden farmers are prohibited from using additional land (Bruun *et al.*, 2009; Vanlauwe *et al.*, 2014). Current yields of swidden farmers are relatively low compared to global average production levels (Bruun *et al.*, 2009). As a result, much research has focused on how yields can be increased and intensified sustainably within swidden agricultural systems (Padoch and Sunderland, 2013). Results from this thesis show which agricultural practices may help to increase and intensify productivity.

7.2.1 Building on existing swidden agricultural practices

Crop pests and relatively infertile soils are often cited as key reasons for swidden farmers' low crop yields, both globally (Oerke, 2006; Johnson and Gurr, 2016; Kukla *et al.*, 2019) and in PNG (Hartemink and Bourke, 2000; Gurr, Liu, *et al.*, 2016). These are not new issues, though, and swidden farmers have already developed practices that allow them to maintain biotic pest control and soil quality. Recognising these practices and researching whether and how they can be translated to more intensely managed systems may be one way to increase and intensify yields.

In Chapter 3, I find that in food gardens along the Mount Wilhelm transect, the levels of foliar herbivory, seed disturbance and pest predation in food gardens are relatively favourable. This may be because along the transect, food gardens are embedded in a forest matrix. This, combined with practices used by swidden farmers along the transect, including burning gardens at the start of a gardening season and planting a wide variety of crops, may be preventing the build-up of pests and enhancing biotic pest control (Bianchi, Booij and Tscharntke, 2006; Kleijn *et al.*, 2019). In areas where farming is intensified, usually only a few crops are planted. This may increase pest problems. Researching whether intercropping in more intensified farming systems is possible, and which crops can best be intercropped would therefore be of interest (Johnson and Gurr, 2016).

In Chapter 4, I find that even though soil quality in the gardens of swidden farmers in Ohu can be improved, it is already able to sustain good yields of sweet potato in both new and fallowed gardens. Current swidden practices, such as making mounds to allow excess moisture to drain away or the burning of vegetation before planting crops, contribute to this (Kukla *et al.*, 2019). When farming is intensified and the same land is used for longer, the practice of burning the land is usually reduced as farmers do not want to risk harming their crops. However, ashes may improve the physiochemical properties of the soil and also help to control pests (Abate, van Huis and Ampofo, 2000; Gay-des-Combes *et al.*, 2017). It may be of interest to research whether ashes from other sources (for example from home fireplaces) can be collected and applied to older fields to enhance soil quality and reduce pests (Bailey, Ramakrishna and Kirchhof, 2008).

7.2.2 Improving swidden agricultural practices

As populations are growing and pressures on land increasing, current practices may not always be sufficient to maintain biotic pest control and soil quality. Therefore it may be worth investigating other options which are not currently widely practised. Farmers may differ in their attitudes towards certain practices or be restricted in what they can do due to a lack of cash, time or access to markets (Bourke and Harwood, 2009; Fujinuma *et al.*, 2018). So it would be useful to research a suite of options that can improve yields.

One option may be to assist farmers with selecting breeding lines. It has been shown that local varieties selected for by swidden farmers may have higher resistance to pests and diseases than more generally-grown varieties, and are adapted to grow well in acid tropical soils (Kokoa, 2001; Johnson and Gurr, 2016; Minemba *et al.*, 2019). Results from Chapter 6 show that farmers in Ohu indeed shift the type and variety of crop they grow depending on which species they deem superior. Building on this, further work on breeding and selecting best cultivars may be beneficial.

It would also be of interest to pay more attention to techniques related to fallow management and forest regeneration (Carneiro da Cunha, 2019). Fallowing helps with pest and weed eradication, soil fertility restoration and can support biodiversity conservation, but little is known about the optimal fallow time and how fallows could best be managed to meet these multiple objectives (Powell *et al.*, 2001; Erni, 2015; Mukul and Herbohn, 2016). One way in which fallows could potentially be improved is by planting tree species which are able to fix nitrogen, phosphorus and potassium into the soil. In some places in PNG people already deliberately cultivate such trees in their fallows, including *Casuarina oligodon*, *Albizia* spp., *Parasponia rigida*, *Piper aduncum* and *Schleinitzia novo-guineensis* (Bourke and Harwood, 2009). Other tree species, such as *Tithonia diversifolia*, *Senna spectabilis, Lantana camara, Gliricidia* and *Leuceana* also have potential to improve soil quality and could be better made use of by farmers (Bailey, Ramakrishna and Kirchhof, 2008). Research could help understand under what conditions what combination of species performs best (Bourke and Harwood, 2009). However, some species, including *Piper aduncum*, *Tithonia diversifolia, Senna spectabilis*, *Lantana camara*, *Gliricidia* and *Leuceana*, have the potential to outcompete native vegetation (CABI, 2021), and it is important to better understand how promoting their use would influence biodiversity conservation objectives.

7.2.3 The whole is greater than the sum of its parts

Often research to increase and intensify yields in the swidden agricultural system focuses on improving individual components, such as increasing biotic pest control or improving soil quality. However, the overall crop production of swidden farmers is dependent on a combination of factors that are interlinked and highly location specific. Trying to improve one component may run the risk of disturbing the system (Abate, van Huis and Ampofo, 2000). For example, improving soil quality by using fertilisers may make crop leaves more attractive to insects and aggravate pest problems (Powell *et al.*, 2001; Oerke, 2006). Or, planting pest- and disease-resistant crops may increase yields temporarily but may eventually cause soils to be depleted as the continued productivity of swidden farming has in part relied on the low net export of nutrients from the soil (Bruun *et al.*, 2009). To ensure that practices are beneficial not only in the short term but also in the long run, it would be beneficial to consider multiple components simultaneously. Also, swidden farmers have long had to balance these different components to make the system work. Researchers aiming to increase and intensify yields should ensure they have a thorough understanding of what swidden farmers do and why, and how their research impacts the entire system rather than an individual component.

7.2.4 *Limits to increasing and intensifying yields*

Based on results from Chapter 3, 4 and 6, it is clear that there is scope to increase and intensify yields on existing agricultural land in PNG. However, some important questions about the benefits of increasing and intensifying yields remain to be answered (Padoch and Sunderland, 2013). For example, more production per unit area may not necessarily spare natural ecosystems. On the contrary, higher yields sometimes lead to more areas being cleared for production due to increased profitability (Barretto *et al.*, 2013). Also, rather than simply focusing on producing more calories, providing more nutritious food is just as important (Welch and Graham, 1999). People in PNG often consume enough calories, but their diets fall short in protein, oil and fat (Bourke and Harwood, 2009; Schmidt, Mueller and Rosenbach, 2020), and it is unclear how increasing yields will help to address this issue. So, increasing and intensifying yields may be one pathway, but not the panacea, for swidden farmers to respond to social-ecological changes. It may thus be useful to also think beyond enhancing productivity, and consider how the social- and economic context in which swidden farmers live and work can be improved (see section 7.4).

7.3 How swidden farmers can achieve change

Swidden farming in PNG has a long and diverse history, which has been characterised by a high degree of innovation and openness to change on the part of farmers (Bourke and Harwood, 2009). In response to population increases, farmers have invented or adopted agricultural practices, such as planting trees in fallows and crop rotations, or taken up new crops, such as sweet potato, cassava and Chinese taro (Bourke and Harwood, 2009). Today farmers are also continuously responding to change (Chapter 6).

However, people may sometimes lack resources when deciding how to respond to ongoing social-ecological changes. Farmers in Ohu indicated that the main barriers they faced included lack of knowledge about agricultural practices, lack of solutions which aligned with their priorities, high initial costs of adoption, and lack of collaboration among themselves (Chapters 4, 5 and 6). Results from this thesis show how these barriers may be overcome.

7.3.1 Making use of social networks to disseminate information

Swidden farmers often lack access to information about ongoing social-ecological changes and potential pathways by which to respond. Farmers in Ohu remarked that they had inadequate knowledge on soil management practices, such as chicken manure and NPK fertiliser (Chapter 4), or on how to tackle cash crop diseases (Chapter 6). Agricultural extension services, which could provide swidden farmers with relevant information, were developed in PNG after World War II and were run by the national government (Bourke and Harwood, 2009). Following Independence in 1975, responsibility for agricultural extension was devolved to the provinces and later to the districts (Sitapai, 2012). A further development occurred in the 1990s when the government set up separate commodity organisations, including for coffee, oil palm, cacao, coconut, food crops and livestock. Finally, there has been a decline in government support for agricultural research and extension services (Sitapai, 2012). The outcome is that there is confusion over lines of authority and responsibility, training is mainly available for individual elements of swidden farming rather than for the system as a whole, and agricultural extension programmes are poorly staffed and resourced (Bourke and Harwood, 2009).

To complement the extension system, there has increasingly been an interest in researching how farmers' social networks can be leveraged to promote information dissemination (Takahashi, Muraoka and Otsuka, 2020). Whether this works and which farmers can best be targeted, depends on the information-sharing relationships among farmers (de Lange, Milner-Gulland and Keane, 2019). I found that swidden farmers in Ohu were not keen to share information and learn from each other, especially not with people outside their clan (Chapter 5). I also showed that providing specific farmers with information altered social structures and dynamics, with those directly involved in the research project becoming more sought-after for advice (Chapter 5). These results may not be unique to PNG, as horticulturalists in Ethiopia were also shown to rely relatively little on social learning compared to pastoralists and urban dwellers (Glowacki and Molleman, 2017). So using farmers' social networks to disseminate agricultural practices may not be straightforward, as people may not always be willing to share information and the intervention may change social structures in unintended ways.

Rather than making use of people's individual networks, a more promising option may be to see to what extent a network of external actors could be leveraged to improve agricultural extension services. In PNG, religious institutions may potentially be of use. Christian churches enjoy legitimacy and support from broad segments of the population (National Statistical Office, 2011). They already play an important role in providing services across PNG; collectively churches provide about half of the country's health services, and in partnership with the government around 40% of primary and secondary education facilities (Hauck, 2010). There have already been some instances in which Christian churches have provided agricultural extension services in PNG, although so far these initiatives have been localised (Bourke and Harwood, 2009). There are examples from other countries in which Christian churches have been successful at disseminating agricultural technologies (Mwangi, Agunga and Garforth, 2003; Andersson and Giller, 2012), and it may be possible to also make this happen in PNG. However, Christian churches are a heterogeneous group of actors, and depending on the interpretation of their religious mandates churches may be more or less willing to get more involved in agricultural extension work (Hauck, 2010). Faith can in some cases also function as a barrier to meaningful agricultural development as certain practices may become seen as 'the only way to farm that is faithful to God', rather than promoting adaptive farm management led by farmers (Andersson and Giller, 2012). It would thus be helpful to research to which extent Christian churches could play a positive role in supporting agricultural extension services in PNG.

7.3.2 Co-designing solutions

Often research related to small-scale farming is done in labs or on research stations, and involves only researchers with little participation from farmers (Stathers *et al.*, 2020). This may cause interventions to be out of sync with farmers' priorities (Danielsen *et al.*, 2009). It is increasingly recognised that if research is to solve real-world problems, it should involve local stakeholders (Mistry and Berardi, 2016). I tried to achieve this by developing the research on soil management practices, as described in Chapter 4, after discussions with farmers in Ohu. I also set up experimental plots on farmers' fields and followed local practices, to make the research as useful to local people as possible. This approach caused the research project to provide an experiential learning opportunity, as I showed in Chapter 5. Even though I involved local stakeholders in the design of the research and data collection, my research was still largely externally driven. This may have caused delays in the rate at which results could be used by local farmers to improve their decision-making and may have reduced their sense of local ownership of the project (Danielsen *et al.*, 2009). Going forward, more extensive collaborations between agricultural researchers and local farmers may be needed, in which local people play an active role across all stages of the research process, including question articulation, sampling design, data collection, data analyses and dissemination.

However, it may not always be straightforward to successfully co-design research, as researchers and farmers may have different goals and expectations (Henning, 2015). Across PNG, there are cases in which local communities have been disappointed with local research projects, as they felt that scientists did not engage in the long-term social relationships that they were hoping for, or did not share the financial benefits of a research project fairly (West, 2006). Also, local perspectives may be diverse as communities are not homogenous (Klein *et al.*, 2014). So involving local stakeholders in a research process should be done on their own terms and in ways that are perceived as beneficial by them, to avoid (unintentional) exploitation (West and Aini, 2021). It will also be important to engage with a range of local actors to capture the many different voices within a community (Klein *et al.*, 2014).

7.3.3 Ensuring solutions are feasible to implement

Another often-faced obstacle for swidden farmers when responding to social-ecological changes is the high cost of implementing an intervention. Farmers in Ohu expressed their concern that, even though they were worried about declining soil fertility, they could not use chicken manure or NPK fertiliser in their gardens because they did not have the required time or money available (Chapters 4 and 5). Lack of time may also be why farmers in Ohu leave their gardens to fallow despite them still giving adequate sweet potato yields (Chapter 4). Across PNG, it has often been observed that swidden farmers abandon a certain crop or practice when farmers believe their return to labour or financial investment is inadequate (Bourke and Harwood, 2009). So it is important to ensure that solutions are actually feasible for farmers to implement.

During the research, farmers started to apply food waste, increased their use of mulching, and began to plant the specific variety of sweet potato that was planted in my experimental gardens (Chapters 4 and 5). This shows that practices that closely link to farmers' current practices are more likely to be taken up, and could lead to promising avenues for future research (Rogers, 2003). Given that swidden agricultural farmers have already developed many agricultural practices which are successful in producing crops in a sustainable way (see section 7.2.1), it would be sensible to see if those practices can be optimised, rather than introducing completely new ones.

Beyond time and money, swidden farmers may perceive additional costs to implementing an agricultural practice. In a blind tasting test, farmers thought that the taste of sweet potatoes harvested from plots to which chicken manure was applied, was less good than that of tubers grown in control plots (Chapter 4). As long as food is not in critical low supply these additional costs may be a barrier to adopting certain agricultural practices (Otieno *et al.*, 2011). Monitoring the intended and unintended effects of interventions may provide insights into what type of agricultural innovations are feasible for farmers to implement, and what barriers they may experience.

7.3.4 Improving collaborations among farmers

Farmers in Ohu pointed out that strong collaborations within their community are needed to overcome barriers and respond to social-ecological changes (Chapter 6). Farmers believe that this may help them to access information and services, and realise new projects. Globally, farmers' organisations have indeed been shown to help small farmers access rural extension services, markets and market information, which can help farmers to improve their income and production quality (Bizikova *et al.*, 2020). However, as highlighted in Chapter 6, there is currently a lack of collaboration among farmers in Ohu. People mainly share information and resources with their direct family (Chapter 5). This may perhaps not be surprising, because farmers mainly rely on help from their direct family, and there is often competition for land-use rights and other resources within and between clans and tribes in PNG (Baynes, Herbohn and Unsworth, 2017). More generally, swidden farming does not necessarily require extensive cooperation between families as subsistence needs can often be met at the household level (Glowacki and Molleman, 2017).

Local governments and technical authorities may have a role to play in building trust among swidden farmers. Active government support, in the form of financial and technical assistance, has been shown be important in making farmer organisations successful (Cramb, 2005; Bizikova *et al.*, 2020). The PNG government is already keen to support agricultural development (National Strategic Plan Taskforce, 2011). One way they could operationalise this commitment is by investing in farmer organisations. Stimulating organisation at a family group level is more likely be successful in PNG than attempting to organise communities at a clan or multi-clan level; Baynes, Herbohn and Unsworth (2017) found that clan-level organisation was prone to failure, while Pamphilon (2019) found that encouraging the formation of family teams worked well. However, care should be taken when promoting farmer organisations, as attempts to modify social traditions can provide dilemmas as well as solutions (Woolcock and Narayan, 2000).

7.4 Beyond swidden farming

Increasingly, swidden farmers across PNG are motivated to diversify from swidden farming as they believe that this may help them to respond to increasing land shortages and climate risks (Schmidt, Mueller and Rosenbach, 2020). Results from this thesis show what opportunities for alternative livelihoods are available to people living in our study area, beyond swidden farming.

7.4.1 Alternative livelihoods and land uses

Traditionally, farmers in PNG have mainly focused on growing crops. However, an increasingly affluent urban population is demanding more animal protein in the form not just of meat, but also milk and eggs (Glatz, 2017). Currently, there is a shortfall in the production of animal protein within PNG and the country is a net importer of these products. So there is an opportunity for local farmers to capitalise on this growth in demand. Farmers in Ohu recognise this, and are indeed thinking about setting up a livestock-rearing project (Chapter 6). However, there are challenges to be overcome, such as ensuring farmers can provide animals with the appropriate nutritional feed and veterinary care (Glatz, 2017), and have access to markets where they can sell their livestock and related products (Bourke and Harwood, 2009).

Swidden farmers in PNG aiming to diversify their livelihoods away from farming have most commonly engaged in informal work so far, while still practising swidden farming on the side. For example, people run stores, provide transportation services or sell handicrafts (Schmidt, Mueller and Rosenbach, 2020). In our interviews for Chapter 6, Ohu residents also indicated that they are increasingly keen to engage in off-farm work. However, women especially face significant challenges when engaging in off-farm work as they may lack access to education and training, face security issues or do not have time due to their domestic work burden. Policies or investments to promote off-farm work should recognise these issues, and if possible, aim to support women to overcome them (Schmidt, Mueller and Rosenbach, 2020).

People are also keen to acquire formal, wage-paying jobs (Chapter 6). Currently, an estimated six percent of the working-age population in PNG is employed in the formal sector (National Strategic Plan Taskforce, 2011). As PNG's economy is growing, opportunities to land a formal job are increasing (Deloitte and UNDP, 2017). However, there is considerable variation across industries and locations in how many job opportunities arise. Currently, white collar firms are hiring more people, and there are considerably more opportunities in Port Moresby (PNG's capital) than in other main cities (Deloitte and UNDP, 2017). Again, women have thus far been disadvantaged when seeking formal employment (National Statistical Office, 2011). So, there may not be equal opportunities for everyone to engage in wage-paying jobs. This is also acknowledged by the PNG government. To tackle this emerging 'them versus us' scenario, the PNG government argues that it will need to improve its service delivery to rural areas, support children to stay in school for longer and address gender inequalities (National Strategic Plan Taskforce, 2011), which is indeed needed.

Increasingly, there are opportunities for swidden farmers to use their land for alternative purposes than swidden farming, such as conservation or mining. Swidden farmers do seriously consider these options as they feel that this may help them to realise community development (Chapter 6). However, many communities struggle to make these choices as they often involve complex trade-offs between conserving their land and forests, retaining the right to access and work their customary lands and achieving alternative livelihoods. Moreover, the trade-offs at play keep changing as a result of ongoing social-ecological changes. Supporting farmers and their communities to pro-actively plan and manage their resources using participatory approaches would be useful to reinforce their capabilities to determine their own futures and strengthen their negotiation position with other parties (Heiner *et al.*, 2019). However, land and resources in PNG are often contested (Baynes, Herbohn and Unsworth, 2017), which may complicate planning processes. So in any planning process all stakeholders should be involved, and there should be structures in place which can help to avoid or resolve potential conflicts.

7.4.2 Improving education

Swidden farmers in Ohu see education as key to responding to social-ecological changes (Chapter 6). On the one hand this is because farmers believe that it would help them to better manage their land, and on the other hand because it would allow them to realise alternative livelihoods.

The current educational system is mainly focused on preparing children to access formal employment. As a result, children who spend more time in education often have to move away from their village, and have reduced knowledge about the local language, biodiversity and farming practices (Kik, 2018). However, given the rapid population growth in PNG and the potentially slow expansion of paid jobs (National Strategic Plan Taskforce, 2011; Deloitte and UNDP, 2017), it may very well be that at least for the foreseeable future paid jobs may not be available to everyone. Those who are left unemployed may still be able to access land via their clan, and could thus revert to swidden farming, informal employment or choose to lease their land for alternative land uses. It would thus be beneficial if at schools there is increased attention paid to enabling students to gain practical knowledge that can be utilised for swidden farming, informal employment and alternative land uses, as well as the more formal knowledge needed for further training or a paid job. This would fit in with remarks from farmers in Ohu that they wish to be educated both to gain formal employment, but also to better manage their land.

7.4.3 Policy recommendations

Today, a large proportion of the population in PNG depends on swidden farming. If the government is to achieve its aim as set-out in *Vision 2050* and related policies (see section 2.2.2.4), it will have to work with farmers. This thesis gives insights into what type of policies may help to build a better future.

Vision 2050 highlights the importance of increasing food production for the domestic market and export crops (National Strategic Plan Taskforce, 2011). To achieve this, the government aims to expand agricultural research and extension. So far, research and extension services in PNG have focused mainly on individual crops (Sitapai, 2012). However, many of the issues that swidden farmers are facing, such as crop disease and land shortages, are not restricted to individual crops but affect the entire farming system (Chapter 6). There is also a huge variety among swidden farming systems within PNG, so it is unlikely that one solution will fit all. To ensure that research and extension services benefit farmers, co-articulation of questions and co-design of solutions between researchers, extension services and farmers will be needed (see sections 7.3.2 and 7.3.3). This will require significant financial investments, and the government should consider building on existing resources and networks (see section 7.3.1), as it already proposes for health and education in *Vision 2050*.

Vision 2050 also highlights the importance of livelihood diversification for farmers. To achieve this, the government is pushing for land registration and land reform to bring more customary land into the formal sector (National Strategic Plan Taskforce, 2011). However, given that resources are often contested in PNG (Baynes, Herbohn and Unsworth, 2017), land registration may lead to conflicts. Also, customary land is currently often undervalued when it is commercialised so land reform may not benefit customary land owners (Anderson, 2010). Farmers point out that to diversify their livelihoods they need enhanced access to education and increase collaboration among themselves (Chapter 6). *Vision 2050* already highlights the importance of improving access to education (National Strategic Plan Taskforce, 2011), but it is also important to ensure that the curriculum fits the needs of farmers and covers both practical and formal knowledge (see section 7.4.2). The government can help foster collaborations by providing financial and technical assistance to farmer organisations (see section 7.3.4).

PNG has experienced positive economic growth over the last couple of decades (The World Bank Group, 2019a), but this has translated into only modest improvements in social indicators (UNDP, 2020b). For *Vision 2050* to achieve its aim, it will be very important to ensure that the majority of people benefit from policies, rather than a few (see section 7.4.1). To achieve this, working with swidden farmers and ensuring their needs are met, will be crucial.

7.5 Lessons learned

Working as an international researcher in PNG has taught me a lot about myself, my own assumptions and my own work (see also section 2.4). In this section I would like to reflect upon the main lessons that I have learned over the past four years, with the aim of carrying them forward into any future work that I may do.

When I first arrived in PNG in 2017, I was hoping that my research could contribute to 'saving the rainforest', and I was predisposed with the desire to 'help' farmers to improve their agricultural practices. I viewed the forest as something inherently good that was separate from us humans and needed protection, and I wanted to achieve this by helping farmers to improve their agricultural practices so they could cut down less forest. Western researchers are often biased towards notions of 'helping' and 'development' (Li, 2007). But as I was conducting my research, I often wondered about who was actually helping who, and where my predisposition came from.

It also became clear to me that my views on how to 'make the world a better place' were different to those of people in PNG. I would sometimes get asked questions which, in my opinion, were far outside the scope of my work as a 'conservationist' or 'agricultural researcher'. For example, people would ask me which church denomination I thought was best. This initially confused me, until I came to understand that to people in Ohu, forests, farming, spirituality and people's well-being are all intertwined. So I had to rethink whose world I was really trying to improve, and how I could actually be useful in doing so. I recognised that instead of wanting to 'help' it was much more useful to establish self-determination as a key principle of engagement (Mistry and Berardi, 2016).

In other instances, I had to admit that my understanding of the system was much more limited than I originally liked to believe. For example, as part of my pilot interviews for Chapter 6 I would ask whether certain animal species had gone extinct. Only later did I realise that for some in PNG the concept of 'extinction' is alien, and that people use different terminology when describing species trends. This and similar experiences led me to explore participatory research methods in which I tried not to put ideas or words in people's mouths.

Furthermore, I learned that if I am, as a researcher, to support people to decide whether and how they want to improve their own world, I will need to ensure that the data and findings of the work are shared with local stakeholders in a way that makes sense to them. When I arrived in Ohu I was often asked why I was there. Originally, my answer was that I was there to collect data and write scientific articles, but I then struggled to reply to follow up questions on how me doing so would actually support the very people I was talking to. Conservation researchers often publish their findings in academic journals, present them at scientific conferences or discuss them on social media, but only a minority of researchers engage in local and regional dissemination practices (Toomey *et al.*, 2019). This can be frustrating for local decision-makers and in certain cases perpetuate legacies of scientific extractivism (Toomey *et al.*, 2019). Throughout my research, I made a point of disseminating the research locally, by discussing preliminary results with local farmers during community meetings, developing a handbook (in English and Tok Pisin) on how to apply compost, manure or NPK fertiliser, presenting my work during seminars at NGBRC and local universities, and visiting local politicians and scientists. Of course, the results of Chapter 5 show that local dissemination can be challenging and have unpredictable results. I tried to mitigate this by leaving ample time for discussions during and after the dissemination event. I also came to recognise that it is more important to understand why potential unintentional effects of information sharing may happen, then refraining from sharing information locally at all.

Besides disseminating the research to people in PNG, I have made an effort to increase awareness about PNG and smallholder farmers within my own community in Europe. People in PNG may still get stereotyped by outsiders as 'living in the past' or 'primitive' (West, 2012, 2016), which is not helpful and may have profound negative effects when external actors try to 'help' farmers in PNG. By writing blog posts (in Dutch) in an online student magazine and participating in a storytelling competition (see https://www.youtube.com/watch?v=6VnHaEh020Y), I tried to make my contribution to pushing against these stereotypes.

Overall, I have come to realise that as a researcher, whether you think of yourself as an ecologist or a social scientist, you and your work are embedded in society. Recognising the different roles that you may play for different people may help you to better understand how your work is shaped by the context in which it takes place, but also allow you to see how your work is shaping that context and how you can positively contribute to it.

7.6 Conclusion

In this thesis I explored how the social-ecological system of swidden farming in PNG is changing, and what interventions may support farmers to respond. Some of these changes, which are rapid and ongoing, include growing populations, climate change and the incursion of external actors, which lead to land use intensification, emerging pests and diseases and deforestation, but also to opportunities to improve current systems and develop alternative livelihoods.

Increasing and intensifying yields can help farmers to respond to growing populations and climate change, while protecting natural ecosystems. Enhancing biotic pest control and improving soil quality using locally available fertilisers can increase and intensify yields, but there is scope to identify additional options. However, there are limits to the usefulness of increasing and intensifying yields, and there is a need to also improve the social- and economic context in which farmers work and live.

It is key to ensure that any proposed intervention is welcomed by swidden farmers. The best way to do this is to work with farmers from the beginning to articulate their needs and design research to answer questions of interest to them. Furthermore, building on existing agricultural and livelihoods practices, rather than introducing completely new concepts, is likely to ensure farmers can implement the proposed solutions. Finally, improving collaborations among farmers may help them to access information and services, and realise ideas they may have.

Farmers are increasingly keen to diversify their livelihoods beyond agriculture, to engage in informal or formal employment, or use their land for other purposes such as conservation or mining. Farmers point out that to succeed in this, they need to have better access to education and the education system should be tailored to their needs.

Change is inherent to swidden farming, and swidden farmers have successfully navigated ongoing changes for many generations. There is hope that they will continue to find ways to respond to social-ecological changes, enabling swidden cultivation to be a viable and sustainable way of living, now and in the future. Researchers can support farmers in these responses, by carrying out interdisciplinary and locally relevant studies in true collaboration with swidden farmers.

Epilogue

Storytelling is engrained in PNG culture (Pascoe, Dressler and Minnegal, 2019). To finish, let me tell you a story and reflect on the meaning of this thesis.

I was born on the branch of a tree. For the first couple of days, I couldn't see. But I could hear my mother land on our branch. 'Open your beak,' she would say, and I would feel something tasty glide down my throat.

After a few days I finally had the energy to open my eyes. There was so much for me to see! Big branches, small branches, big green leaves and lots of fruits. It was a nice, clear view!

One day I was sitting on my tree branch, waiting for my mother. But as I was watching over my forest, some tree branches started to move. After a while, a white cloud came from below. It smelled like my tree branch, but a bit different too. I could no longer see clearly. My mother returned. 'Smoke,' she said, 'Sometimes humans do that. They burn branches like the one we live on.' 'Why?' I asked her. 'So they can grow back other branches, which they can eat. Humans are like us, they need to eat too. But whenever you see smoke, you need to move, because if you are not careful, it can trap you. It is time for you to fly and see beyond the smoke.'

So I spread my wings and flew away. But then I got tired. I had just gotten used to my new tree branch when I heard a noise. I looked down and I saw people. 'Right tree, top branch, left,' one of them said, 'be silent, you may chase him away.' That's where I am, I thought, do they want to rest on my branch too? But they didn't. They just sat below my tree and kept looking at me. Whenever I moved a wing, one of them started to scribble things down in a big book. After a while, the sun had moved and I too decided to hop over to another branch so I could catch the last sunrays of the day. The people moved with me, and they continued scribbling. These people really are strange creatures, I thought to myself. When the sun had gone, the people moved around and started to gather small tree branches and make a fire. Not before long, a small white cloud came my way - smoke. Time to move.

The next humans I saw, did not carry big books but massive machines. I had never seen this, and I decided to stop and look. But I didn't get to sit down for long. The machines started to make lots of noise, many tree branches started to move, and then lots of smoke arose. I flew up. It was only then that one of the people looked up and saw me. 'Look!' he said. Too late, I thought.

Where have all the trees gone? I had to fly for hours before there was a decent tree branch for me again. I landed. I had just cleaned my beak when I realised that many humans were staring at me. Do people not have any sense of privacy anymore?! Then some of them took out little machines and started to focus them on me. 'One photo, two kina,' I heard one of them say. That person then took out a cigarette, lit it and put it in his mouth. Smoke came from it. I could no longer stay.

I decided to return home, because no tree branch I had landed on felt like the tree branch that I was born on. I sat down next to my mother. In the distance, we could see some humans walking around their branches, while we sat on ours. We ate our favourite foods, and I told her about all the small and big smokes that I had seen. 'How come there are so many different types of smoke? Is there a best one?' I asked her. 'As people change, their smoke changes,' she answered, 'But if you stay long enough, then even the smallest smoke may trap you and you won't be able to see anymore.'

At night, some people started to dress up. They put feathers, like the ones we have, on their bodies. They started to move, like we can dance too. 'Don't be so surprised,' my mother said, 'I told you. These humans, they are like us. And that's the best, because it means that they too can fly and see beyond the smoke.'

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- Appendices -

Appendix A – Supplementary material for Chapter 3

A - Table 1 | Overview of sampling intensity per crop per village. NM stands for not measured.

Plant species	Village	Predation (number of artificial caterpillars set out)	Disturbance of large seeds (number of seeds set out)	Disturbance of small seeds (number of seeds set out)	Foliar herbivory (number of leaf frames)
Banana	Kausi	9 x 20	5 x 2 x 20	5 x 2 x 20	11
	Numba	6 x 20	9 x 2 x 20	9 x 2 x 20	4
	Bundikra	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Sinopas	5 x 20	5 x 2 x 20	5 x 2 x 20	4
	Pomiai	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Kegesuglo	NM	NM	NM	NM
Cassava	Kausi	8 x 20	5 x 2 x 20	5 x 2 x 20	10
	Numba	5 x 20	9 x 2 x 20	9 x 2 x 20	4
	Bundikra	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Sinopas	NM	NM	NM	NM
	Pomiai	NM	NM	NM	NM
	Kegesuglo	NM	NM	NM	NM
Chayote	Kausi	NM	NM	NM	NM
	Numba	4 x 20	7 x 2 x 20 + 1 x 1 x 20	7 x 2 x 20 + 1 x 1 x 20	3

	Bundikra	5 x 20	5 x 2 x 20	5 x 2 x 20	4
	Sinopas	5 x 20	5 x 2 x 20	5 x 2 x 20	4
	Pomiai	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Kegesuglo	NM	NM	NM	NM
Chinese taro	Kausi	5 x 20	3 x 2 x 20 + 1 x 1 x 20	3 x 2 x 20 + 1 x 1 x 20	6
	Numba	5 x 20	9 x 2 x 20	9 x 2 x 20	4
	Bundikra	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Sinopas	4 x 20	5 x 2 x 20	5 x 2 x 20	4
	Pomiai	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Kegesuglo	NM	NM	NM	NM
Sugarcane	Kausi	7 x 20	6 x 2 x 20	6 x 2 x 20	10
	Numba	5 x 20	9 x 2 x 20	9 x 2 x 20	4
	Bundikra	NM	NM	NM	NM
	Sinopas	5 x 20	5 x 2 x 20	5 x 2 x 20	4
	Pomiai	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Kegesuglo	NM	NM	NM	NM
Sweet potato	Kausi	8 x 20	5 x 2 x 20	5 x 2 x 20	11
	Numba	6 x 20	9 x 2 x 20	9 x 2 x 20	4
	Bundikra	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Sinopas	5 x 20	5 x 2 x 20	5 x 2 x 20	4
	Pomiai	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Kegesuglo	5 x 20	5 x 2 x 20	5 x 2 x 20	5
Taro	Kausi	NM	NM	NM	NM

	Numba	5 x 20	9 x 2 x 20	9 x 2 x 20	4
	Bundikra	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Sinopas	5 x 20	5 x 2 x 20	5 x 2 x 20	4
	Pomiai	5 x 20	5 x 2 x 20	5 x 2 x 20	5
	Kegesuglo	NM	NM	NM	NM
Highland kapiak	Kausi	NM	NM	NM	NM
	Numba	NM	NM	NM	NM
	Bundikra	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Sinopas	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Pomiai	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Kegesuglo	1 x 100	10 x 1 x 20	10 x 1 x 20	5
Kumu musong	Kausi	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Numba	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Bundikra	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Sinopas	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Pomiai	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Kegesuglo	NM	NM	NM	NM
Tulip	Kausi	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Numba	1 x 100	10 x 1 x 20	10 x 1 x 20	5
	Bundikra	NM	NM	NM	NM
	Sinopas	NM	NM	NM	NM
	Pomiai	NM	NM	NM	NM
	Kegesuglo	NM	NM	NM	NM

A - Table 2 | Overview of response variables, type of data, type of regression and independent variables for models fitted in gardens and forests.

			Predation of insect herbivores	**Seed disturbance**	**Foliar herbivory**
Type of data			Count of attacked and unattacked caterpillars	Count of disturbed and undisturbed seeds	Percentage of foliar herbivory
Type of regression			Binomial	Binomial	Beta
Independent variables	Gardens	Plant type	✓	✓	✓
		Elevation	✓	✓	✓
		$Elevation^2$			✓
		Garden area	✓	✓	✓
		Crop richness	✓	✓	✓
		Garden age	✓	✓	✓
	Forests	Plant type	✓	✓	✓
		Elevation	✓	✓	✓
		$Elevation^2$			✓
	Gardens vs. forests	Elevation	✓	✓	✓
		$Elevation^2$			✓
		Gardens vs. forests	✓	✓	✓

A - Table 3 | Overview of the study sites. In 'Plant types', dark grey shading indicates that crops were present, whereas light red shading indicates that crops were absent.

			Kausi	Numba	Bundikra	Sinopas	Pomiai	Kegesuglo
Plant type	Gardens	Banana	■	■	■	■	■	□
		Cassava	■	■	■	□	□	□
		Chayote	□	■	■	■	■	□
		Chinese taro	■	■	■	■	■	□
		Sugarcane	■	■	□	■	■	□
		Sweet potato	■	■	■	■	■	■
		Taro	□	■	■	■	■	□
	Forests	Highland kapiak	□	□	■	■	■	■
		Kumu musong	■	■	■	■	■	□
		Tulip	■	■	□	□	□	□
Elevation (m)	Gardens		174	756	1471	1895	1954	2669
	Forests		188	703	1443	1917	1752	2685
Garden area (m^2)	Gardens		1409	797	521	373	935	499
Garden crop richness (mean number of crops)	Gardens		12	15	15	11	11	11
Garden age (mean number of years)	Gardens		3.2	2.2	4.1	2.1	2.2	2.4

A - Table 4 | Overview of the different crop species found in gardens along the Mount Wilhelm gradient. Those species highlighted in bold were found during the main study. Species not highlighted were found during a wider sample of gardens.

	Plant species (scientific name)	Plant species (common English name)	Minimum altitude (m)	Maximum altitude (m)
1	***Abelmoschus manihot***	**Aibika**	**180**	**2179**
2	*Allium cepa var. cepa*	Onion	2035	2752
3	***Allium fistulosum***	**Spring onion**	**756**	**2669**
4	*Allium sativum*	Garlic	2752	2752
5	***Amaranthus dubius***	**Chinese spinach**	**198**	**2179**
6	***Ananas sativus***	**Pineapple**	**180**	**2228**
7	*Anonna muricata*	Soursop	748	748
8	*Apium graveolens var. dulce*	Celery	2557	2752
9	***Apium sp. 1***	**Water lettuce**	**198**	**2752**
10	***Apium sp. 2***	**Species of salad**	**2669**	**2752**
11	***Arachis hypogea***	**Peanut**	**185**	**789**
12	***Areca catechu***	**Betel nut**	**180**	**787**
13	***Areca macrocalyx***	**Kavivi**	**1521**	**2079**

14	*Artocarpus communis*	Bread fruit	198	789
15	*Asparagus officinalis*	Asparagus	2228	2752
16	*Bambusa sp.*	Bamboo	2079	2439
17	*Brassica oleracea*	Broccoli	2127	2752
18	***Brassica oleracea var. botrytis***	**Cauliflower**	**2557**	**2630**
19	***Brassica oleracea var. capitata***	**Round cabbage**	**2127**	**2752**
20	*Breynia sp.*	Breynia	198	789
21	*Bryophyllum pinnatum*	Air plant	198	198
22	***Capsicum frutescens***	**Chilli**	**198**	**789**
23	***Carica papaya***	**Papaya**	**180**	**789**
24	*Casuarina oligodon*	She-oak	2079	2079
25	*Cinnamomum cullilawan*	Cinnamon	775	775
26	*Citrullus lanatus var. lanatus*	Water melon	2056	2056
27	*Citrus reticulata*	Mandarin	783	789
28	*Clausena papuana*	Citrus variety (Tok Pisin: curry diwai)	198	198
29	***Cocos nucifera***	**Coconut**	**180**	**784**

30	***Coffea arabica***	**Coffee**	**775**	**1548**
31	***Colocassia esculenta***	**Taro**	**748**	**2565**
32	*Coriandrum sativum*	Coriander	2630	2630
33	*Cucumis cf. myriocarpus*	Cucumber	1927	2439
34	***Curcubita moschata***	**Pumpkin**	**185**	**2557**
35	*Curcubita pepo*	Zucchini	2056	2557
36	*Curcuma longa*	Tumeric	775	775
37	***Cyathea contaminans***	**Fern**	**2079**	**2127**
38	*Cyathea sp.*	Small fern (Tok Pisin: pogu)	1521	2228
39	*Cymbopogon cistratus*	Lemon grass	2035	2579
40	*Cyphomandra batacea*	Tree tomato	2136	2228
41	*Daucus carota*	Carrot	2565	2752
42	***Dioscorea bulbifera***	**Wild yam**	**174**	**756**
43	***Dioscorea esculanta***	**Yam**	**180**	**784**
44	***Ficus copiosa***	**Kumu musong**	**185**	**1927**
45	*Ficus dammaropsis*	Highland kapiak	1523	2630

46	*Ficus wassa*	Fig leaves	180	2228
47	***Fragaria ananassa***	**Strawberry**	**2565**	**2752**
48	***Glycine max***	**Soy bean**	**787**	**2565**
49	***Gnetum gnemon***	**Tulip**	**180**	**789**
50	***Ipomea batatas***	**Sweet potato**	**180**	**2630**
51	***Iresine herbstii***	**Bloodleaf**	**748**	**2439**
52	***Lablab purpureus***	**Roots bean/Hyacinth bean**	**1548**	**2228**
53	***Lactuca sativa***	**Lettuce**	**2079**	**2179**
54	*Laportea decumana*	Salat	775	2056
55	*Malus domestica*	Apple	2630	2630
56	***Mangifera minor***	**Mango**	**180**	**789**
57	***Manihot esculenta***	**Cassava**	**180**	**2579**
58	*Moringa oleifera*	Moringa	185	185
59	***Musa spp. Cultivars***	**Banana**	**180**	**2579**
60	***Nasturtium officinale***	**Watercress**	**756**	**2669**
61	*Nephelium lappaceum*	Rambutan	198	784

62	*Nicotiana tobaccum*	Tobacco	784	2136
63	*Ocimum basilicum*	Basil	2439	2439
64	***Pandanus conoideus***	**Marita**	**1548**	**1548**
65	*Pandanus julianetti*	Species of pandanus (Tok Pisin: karuka)	180	2439
66	*Pangium edule*	Football fruit	775	784
67	*Passiflora ligularis*	Sweet granadilla	1927	2439
68	*Passiflora mollissima*	Banana passion fruit	2035	2179
69	*Pedilanthus tithymaloides*	Redbird flower	198	198
70	*Persea americana*	Avocado	748	2630
71	*Petroselinum crispum*	Parsley	783	2752
72	***Phaseolus vulgaris***	**Greasy bean**	**2669**	**2669**
73	*Pinus patula*	Pine tree	2079	2079
74	*Piper betel*	Mustard	198	789
75	*Piper methysticum*	Kava	198	198
76	***Pisum sativum***	**Peas**	**2079**	**2579**
77	*Prunus avium*	Cherry	2752	2752

78	*Psidium guajava*	Guava	783	784
79	***Raphanus sativus***	**White radish**	**2752**	**2752**
80	*Rubus fruticosus*	Blackberry	2127	2127
81	***Rungia klossii***	**Rungia**	**1471**	**1954**
82	***Saccharum officinarum***	**Sugarcane**	**180**	**2557**
83	***Saccharum robustum***	**Pitpit**	**784**	**2630**
84	***Saccharum sp. 1***	**Highland pitpit**	**789**	**789**
85	***Sechium edule***	**Chayote**	**775**	**2752**
86	***Solanum lycopersicum***	**Tomato**	**783**	**2557**
87	*Solanum nigrum*	Black nightshade	2557	2557
88	***Solanum tuberosum***	**Potato**	**2127**	**2752**
89	*Symphytum officinale*	Comfrey	2439	2579
90	*Terminalia kaernbachii*	Okari nut	180	180
91	***Theobroma cacao***	**Cacao**	**185**	**789**
92	*Vanilla planifolia*	Vanilla	775	775
93	***Vicia faba***	**Broad bean**	**2056**	**2752**

94	***Vigna unguiculata ssp. sesquipedalis***	**Snake bean**	**180**	**2630**
95	***Xanthosoma sagittifolium***	**Chinese taro**	**180**	**2228**
96	***Zea mays***	**Corn**	**180**	**2579**
97	***Zingiber officinale***	**Ginger**	**180**	**2079**

A - Table 5 | Overview of the level of the different ecosystem services (predation of insect herbivores) and disservices (seed disturbance and foliar herbivory) in gardens measured along the elevational gradient. Data were pooled across crops with mean percentage ± s.e. shown.

Village (m elevation)	Predation of insect herbivores (%)	Seed disturbance – large seeds (%)	Seed disturbance – small seeds (%)	Foliar herbivory (%)
Kausi (174)	14 ± 1.5	9.4 ± 4.7	65 ± 4.9	0.73 ± 0.17
Numba (756)	6.7 ± 1.3	5.5 ± 1.6	62 ± 3.5	0.57 ± 0.15
Bundikra (1471)	5.5 ± 1.6	3.6 ± 1.8	73 ± 5.0	1.4 ± 0.30
Sinopas (1895)	3.1 ± 1.1	0.58 ± 0.23	77 ± 6.1	1.5 ± 0.43
Pomiai (1954)	1.7 ± 1.0	0.083 ± 0.083	67 ± 5.9	1.1 ± 0.40
Kegesuglo (2669)	0	1.5 ± 1.0	85 ± 7.8	0.68 ± 0.39

A - Table 6 | Overview of the level of the different ecosystem services (predation of insect herbivores) and disservices (seed disturbance and foliar herbivory) in gardens measured for different crop species. Data were pooled across village with mean percentage ± s.e. shown.

Crop	Predation of insect herbivores (%)	Seed disturbance –large seeds (%)	Seed disturbance – small seeds (%)	Foliar herbivory (%)
Banana	7.3 ± 1.5	6.3 ± 2.7	59 ± 5.3	1.2 ± 0.34
Cassava	12 ± 2.4	1.8 ± 0.78	74 ± 5.4	0.58 ± 0.19
Chayote	5.5 ± 2.1	1.6 ± 0.75	69 ± 6.0	0.69 ± 0.18
Chinese taro	8.7 ± 2.5	7.3 ± 4.0	61 ± 5.7	0.98 ± 0.41
Sugarcane	4.4 ± 1.6	1.9 ± 1.1	71 ± 5.9	0.69 ± 0.21
Sweet potato	5.8 ± 1.2	5.1 ± 2.3	76 ± 4.7	0.93 ± 0.15
Taro	1.0 ± 0.46	1.4 ± 0.94	68 ± 6.6	1.8 ± 0.68

A - Table 7 | Overview of the level of the different ecosystem services (predation of insect herbivores) and disservices (seed disturbance and foliar herbivory) in forests measured along the elevational gradient. Data were pooled across plant type with mean percentage ± s.e. shown.

Village (m elevation)	Predation of insect herbivores (%)	Seed disturbance– large seeds (%)	Seed disturbance – small seeds (%)	Foliar herbivory (%)
Kausi (188)	17 ± 0.50	1.0 ± 0.78	84 ± 6.7	4.6 ± 1.1
Numba (703)	8.5 ± 2.5	3.5 ± 2.1	96 ± 2.3	7.8 ± 0.96
Bundikra (1443)	7.0 ± 4.0	5.0 ± 2.6	93 ± 2.4	5.7 ± 1.3
Sinopas (1917)	3.0 ± 0	1.3 ± 0.62	66 ± 7.8	2.9 ± 0.55
Pomiai (1752)	5.0 ± 0.025	0.25 ± 0.25	87 ± 4.8	3.2 ± 0.99
Kegesuglo (2685)	0	0	57 ± 11	0.080 ± 0.039

A - Table 8 | Overview of the level of the different ecosystem services (predation of insect herbivores) and disservices (seed disturbance and foliar herbivory) in forests measured for different wild plants. Data were pooled across village with mean percentage ± s.e. shown.

Plant	Predation of insect herbivores (%)	Seed disturbance – large seeds (%)	Seed disturbance – small seeds (%)	Foliar herbivory (%)
Highland kapiak	2.8 ± 1.0	2.6 ± 1.4	83 ± 4.2	2.6 ± 0.87
Kumu musong	9.2 ± 2.3	1.1 ± 0.64	78 ± 4.4	5.4 ± 0.71
Tulip	12 ± 5.5	3.0 ± 1.7	93 ± 3.2	5.5 ± 0.66

A - Table 9 | Overview of response variables, type of data, type of regression and independent variables for models fitted in gardens and forests.

	Predation of insect herbivores	**Seed disturbance – large**	**Seed disturbance – small**	**Foliar herbivory**
		Gardens		
Plant type	All crop comparisons $p > 0.05$	All crop comparisons $p > 0.05$	All crop comparisons $p > 0.05$	All crop comparisons $p > 0.05$
Elevation	ß = -0.00098, $t(156) = -5.0$, $p < 0.001$	ß = -0.0012, $t(171) = -3.2$, $p = 0.0019$	ß = 0.00044, $t(171) = 2.7$, $p = 0.0088$	ß = 0.00065, $t(150) = 1.4$, $p = 0.16$
Elevation^2				ß = -0.00000025 $t(150) = -1.3$, $p = 0.20$
Garden area	ß = -0.00015, $t(156) = -0.80$, $p = 0.42$	ß = 0.00033, $t(171) = 1.2$, $p = 0.23$	ß = 0.00019, $t(171) = 1.2$, $p = 0.24$	ß = -0.00011, $t(150) = -0.93$, $p = 0.35$
Crop richness	ß = 0.0054, $t(156) = 0.16$, $p = 0.88$	ß = 0.095, $t(171) = 1.5$, $p = 0.13$	ß = 0.091, $t(171) = 3.0$, $p = 0.0032$	ß = -0.028, $t(150) = -1.3$, $p = 0.18$
Garden age	ß = 0.13, $t(156) = 1.9$, $p = 0.064$	ß = -0.028, $t(171) = -0.23$, $p = 0.82$	ß = 0.014, $t(171) = 0.20$, $p = 0.84$	ß = 0.041, $t(150) = 0.77$, $p = 0.44$

		Forests		
Plant type	All wild plant comparisons $p > 0.05$	All wild plant comparisons $p > 0.05$	Highland kapiak > kumu musong ß = -1.2, z = -2.3, p = 0.047	Highland kapiak < kumu mosong ß = 0.67, t(49) = 2.7, p = 0.027
Elevation	ß = -0.00090, t(7) = -3.6, p = 0.0089	ß = -0.00095, t(106) = -1.3, p = 0.18	ß = -0.0012, t(106) = -3.0, p = 0.0030	ß = 0.0013, t(49) = 2.7, p = 0.010
$Elevation^2$				ß = -0.00000072 t(49) = -3.4, p = 0.0016
		Gardens vs. forests		
Elevation	ß = -0.0010 t(175) = -7.3, p < 0.001	ß = -0.0010 t(289) = -3.6, p = 0.00041	ß = -0.000087 t(289) = -0.69, p = 0.49	ß = 0.0011 t(213) = 3.9, p < 0.001
$Elevation^2$				ß = -0.00000058 t(213) = -4.6, p < 0.001
Gardens vs. forests	ß = 0.25, t(175) = 1.2, p = 0.24	ß = -0.65, t(289) = -1.6, p = 0.11	ß = 0.82, t(289) = 4.1, p < 0.001	ß = 1.3, t(213) = 9.4, p < 0.001

Appendix B – Supplementary material for Chapter 4

B - Table 1 | Amount of nitrogen, phosphorus, potassium and water in banana peels, chicken manure and NPK fertiliser.

	N (%)	P (%)	K (%)	H_2O (%)
Banana peels	0.81	0.10	17	84
Chicken manure	2.9	1.2	8.6	79
NPK fertiliser	12	12	17	-

B - Table 2 | Overview of the models run on the split data set for new and fallowed gardens.

Response variable	**Type of data**	**Distribution**	**Model**				
			Fixed effects			*Random effect*	
			Treatment	*Mound type*	*Harvest*	*Garden*	*Plot*
Soil moisture	Percentage per mound / 100 *Semi-continuous*	Beta	✓		✓	✓	✓
Soil nutrients	pH, available N, P and K, and total N, P and K *Semi-continuous*	Normal	✓		✓	✓	
Leaf yield	Weight in grams per mound *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓
Vine yield	Weight in grams per mound *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓
Tuber yield	Weight in grams per mound *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓
Tuber number	Number of tubers per mound *Count*	ZA poisson	✓	✓	✓	✓	✓

B - Table 3 | Overview of the models run on the full data set with an interaction effect between treatment and garden type where applicable.

Response variable	Type of data	Distribution	Model							
			Fixed effects				*Interaction effect*	*Random effect*		
			Treatment	*Garden type*	*Mound type*	*Harvest*	*Treatment * Garden type*	*Garden*	*Plot*	*Mound*
Soil moisture Time 0	Percentage per mound / 100 *Semi-continuous*	Beta	✓	✓				✓	✓	
Soil moisture	Percentage per mound / 100 *Semi-continuous*	Beta	✓	✓		✓	✓	✓	✓	
Soil nutrients Time 0	pH, available N, P and K, and total N, P and K *Semi-continuous*	Gamma	✓	✓				✓		
Soil nutrients	pH, available N, P and K, and total N, P and K *Semi-continuous*	Normal	✓	✓		✓	✓	✓		
Plant nutrients	Total N, P, K and C *Semi-continuous*	Normal	✓	✓		✓	✓	✓		
Tuber nutrients	Total N, P, K and C *Semi-continuous*	Normal	✓			✓				

Tuber quality	Rank on a 0-1 scale per tuber *Factorial*	Binomial logistic	✓	✓	✓	✓	✓	✓	✓	✓
Leaf yield	Weight in grams per mound *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓	✓	✓	
Vine yield	Weight in grams per mound *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓	✓	✓	
Tuber yield	Weight in grams per mound *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓	✓	✓	
Weight per tuber	Weight in grams per tuber *Semi-continuous*	ZA gamma	✓	✓	✓	✓	✓	✓	✓	✓
Tuber number	Number of tubers per mound *Count*	ZA poisson	✓	✓	✓	✓	✓	✓	✓	
Taste	Rank *Ordinal*	Ordinal	✓			✓				

B - Table 4 | Hypothesized mechanisms based on a priori knowledge with → indicating a positive correlation, — no effect, and - - -→ a negative correlation.

Path			Hypothesized mechanisms
Treatments	→	Soil nutrients	I expected compost to mainly increase the amount of available potassium, chicken manure the amount of available nitrogen and NPK fertilizer the amount of available nitrogen and phosphorus.
Treatments	→ —	Soil moisture	Compost and chicken manure increase soil moisture (Amanullah, Sekar and Muthukrishnan, 2010; Gay-des-Combes *et al.*, 2017), while NPK fertilizer does not affect soil moisture (Tadesse *et al.*, 2013; Bassouny and Chen, 2015).
Soil moisture	→ - - -→	Tuber yield	Too dry or to wet conditions inhibit tuber development. Soil moisture of 17-20% is ideal for sweet potato tuber development (Gajanayake *et al.*, 2013).
Soil nutrients	→	Tuber yield	Tuber formation is mainly depended upon nitrogen (Bourke, 1985).
Total plant biomass	- - -→	Soil moisture	Increased plant biomass stores more water and increases evapotranspiration causing soil moisture to decrease (Bhatt and Hossain, 2019).

B - Table 5 | Regressions included in the structural equation model. Treatment and garden type were coded as dummy variables with 'Control' and 'New garden' as the reference levels. A linear distribution had to be fitted to the soil moisture data, as it is currently not possible to fit a beta distribution in the piecewiseSEM package (Lefcheck, Byrnes and Grace, 2019).

Response variable	**Distri-bution**	**Fixed effects**											**Random effect**
		Compost	*Manure*	*NPK fertiliser*	*Fallowed garden*	*Harvest 2*	*Harvest 3*	*Total plant biomass*	*Soil available N*	*Soil available P*	*Soil available K*	*Soil moisture*	*Garden*
Soil available N	Normal	✓	✓	✓	✓	✓	✓						✓
Soil available K	Normal	✓	✓	✓	✓	✓	✓						✓
Soil available P	Normal	✓	✓	✓	✓	✓	✓						✓
Soil moisture	Normal	✓	✓	✓	✓	✓	✓	✓					✓
Tuber yield	Gamma	✓	✓	✓	✓	✓	✓	Correlated	✓	✓	✓	✓	✓

B - Table 6 | Model results from the models on soil nutrients and soil moisture at the start of the experiment, before fertilisers were applied or sweet potato plants planted. Reference levels are given in grey shading for each variable.

		Soil available N	**Soil total N**	**Soil available P**	**Soil total P**	**Soil available K**	**Soil total K**	**Soil moisture**
Treatment	Control							
	Compost	ß = -0.19 t(35) = -1.3 p = 0.20	ß = -0.014 t(27) = -0.26 p = 0.80	ß = 0.0075 t(26) = 0.034 p =0.97	ß = 0.21 t(31) = 1.9 p = 0.071	ß = -0.065 t(26) = -0.91 p = 0.37	ß = -0.0086 t(26) = -0.12 p = 0.90	ß = -0.058 t(176) = -1.6 p = 0.10
	Chicken manure	ß = -0.052 t(35) = -0.36 p = 0.72	ß = -0.013 t(27) = -0.24 p = 0.81	ß = 0.31 t(26) = 1.4 p = 0.17	ß = 0.22 t(31) = 1.9 p = 0.061	ß = -0.021 t(26) = -0.30 p = 0.77	ß = 0.12 t(26) = 1.7 p = 0.10	ß = -0.0023 t(176) = -0.064 p = 0.95
	NPK fertiliser	ß = -0.12 t(35) = -0.82 p = 0.42	ß = 0.018 t(27) = 0.34 p = 0.74	ß = 0.38 t(26) = 1.7 p = 0.094	ß = 0.21 t(31) = 1.9 p = 0.073	ß = 0.055 t(26) = 0.77 p = 0.45	ß = 0.18 t(26) = 2.6 p = 0.015	ß = -0.045 t(176) = -1.3 p = 0.21
Garden type	New							
	Fallowed	ß = -0.30 t(35) = -2.9 p = 0.0059	ß = 0.086 t(27) = 2.3 p = 0.028	ß = -1.1 t(26) = -6.5 p < 0.001	ß = -0.17 t(31) = -2.1 p = 0.043	ß = -0.54 t(26) = -11 p < 0.001	ß = -0.12 t(26) = -2.4 p = 0.026	ß = 0.095 t(176) = 3.8 p < 0.001

B - Table 7 | Model results from the model which tests the effect of location of measurement on soil nutrients and soil moisture. The reference level is given in grey shading.

		Soil available N	**Soil total N**	**Soil available P**	**Soil total P**	**Soil available K**	**Soil total K**	**Soil moisture**
Location	In between mounds							
	Mounds	ß = 4.2 t(226) = 9.5 p < 0.001	ß = 499 t(226) = 6.2 p < 0.001	ß = 14 t(226) = 7.2 p < 0.001	ß = 175 t(226) = 8.9 p < 0.001	ß = 51 t(226) = 5.9 p < 0.001	ß = 785 t(226) = 5.1 p < 0.001	ß = -0.78 t(1135) = -41 p < 0.001

B - Table 8 | Model results from the models on soil nutrients and soil moisture in new gardens and fallowed gardens separately at harvests 1, 2 and 3. Reference levels are given in grey shading for each variable.

		Soil available N	**Soil total N**	**Soil available P**	**Soil total P**	**Soil available K**	**Soil total K**	**Soil moisture**
					New gardens			
Treatment	Control							
	Compost	ß = 0.60 t(47) = 0.46 p = 0.65	ß = 205 t(47) = 1.4 p = 0.18	ß = 2.6 t(47) = 0.44 p = 0.66	ß = -37 t(47) = -0.64 p = 0.52	ß = 60 t(47) = 2.1 p = 0.043	ß = 633 t(47) = 2.0 p = 0.056	ß = -0.086 t(281) = -1.7 p = 0.089
	Chicken manure	ß = 4.3 t(47) = 3.2 p = 0.0023	ß = 409 t(47) = 2.7 p = 0.010	ß = 22 t(47) = 3.6 p < 0.001	ß = 154 t(47) = 2.7 p = 0.011	ß = -16 t(47) = -0.55 p = 0.59	ß = 507 t(47) = 1.5 p = 0.13	ß = -0.16 t(281) = -3.3 p = 0.0011
	NPK fertiliser	ß = 0.84 t(47) = 0.61 p = 0.55	ß = 309 t(47) = 2.0 p = 0.054	ß = 37 t(47) = 5.9 p < 0.001	ß = 194 t(47) = 3.3 p = 0.0020	ß = 17 t(47) = 0.57 p = 0.57	ß = 733 t(47) = 2.2 p = 0.035	ß = -0.24 t(281) = -4.8 p < 0.001
Harvest	Harvest 1							
	Harvest 2	ß = 1.2 t(47) = 1.1 p = 0.28	ß = -278 t(47) = -2.1 p = 0.037	ß = 5.5 t(47) = 1.0 p = 0.30	ß = -21 t(47) = -0.42 p = 0.67	ß = 38 t(47) = 1.5 p = 0.13	ß = 461 t(47) = 1.6 p = 0.11	ß = 0.18 t(281) = 4.1 p < 0.001
	Harvest 3	ß = -1.7 t(47) = -1.4 p = 0.15	ß = -129 t(47) = -0.94 p = 0.35	ß = 6.9 t(47) = 1.3 p = 0.21	ß = 88 t(47) = 1.7 p = 0.094	ß = -12 t(47) = -0.48 p = 0.64	ß = 262 t(47) = 0.89 p = 0.38	ß = -0.30 t(281) = -6.6 p < 0.001

		Fallowed gardens						
Treatment	Control							
	Compost	ß = -0.094 t(50) = -0.066 p = 0.95	ß = 85 t(50) = 0.48 p = 0.64	ß = -3.2 t(50) = -0.52 p = 0.61	ß = 77 t(50) = 1.8 p = 0.077	ß = 97 t(50) = 3.8 p < 0.001	ß = -146 t(50) = -0.32 p = 0.75	ß = -0.18 t(271) = -3.0 p = 0.0026
	Chicken manure	ß = 2.3 t(50) = 1.6 p = 0.12	ß = -69 t(50) = -0.39 p = 0.70	ß = 14 t(50) = 2.2 p = 0.034	ß = 71 t(50) = 1.7 p = 0.10	ß = -23 t(50) = -0.88 p = 0.39	ß = 369 t(50) = 0.80 p = 0.43	ß = -0.065 t(271) = -1.2 p = 0.25
	NPK fertiliser	ß = 0.15 t(50) = 0.10 p = 0.92	ß = -81 t(50) = -0.45 p = 0.65	ß = 11 t(50) = 1.7 p = 0.092	ß = 144 t(50) = 3.4 p = 0.0015	ß = 31 t(50) = 1.2 p = 0.24	ß = 122 t(50) = 0.26 p = 0.79	ß = -0.22 t(271) = -3.8 p < 0.001
Harvest	Harvest 1							
	Harvest 2	ß = 3.3 t(50) = 2.7 p = 0.0097	ß = -277 t(50) = -1.8 p = 0.078	ß = 10 t(50) = 1.9 p = 0.064	ß = -28 t(50) = -0.74 p = 0.46	ß = 44 t(50) = 2.0 p = 0.056	ß = -733 t(50) = -1.8 p = 0.073	ß = 0.15 t(271) = 3.1 p = 0.0023
	Harvest 3	ß = 0.71 t(50) = 0.57 p = 0.57	ß = -243 t(50) = -1.6 p = 0.12	ß = 8.9 t(50) = 1.6 p = 0.11	ß = 1.6 t(50) = 0.042 p = 0.97	ß = 14 t(50) = 0.65 p = 0.52	ß = 78 t(50) = 0.20 p = 0.85	ß = -0.22 t(271) = -4.2 p < 0.001

B - Table 9 | Model results from the models with an interaction between treatment and garden type on soil nutrients and soil moisture at harvests 1, 2 and 3. Reference levels are given in grey shading for each variable.

		Soil available N	Soil total N	Soil available P	Soil total P	Soil available K	Soil total K	Soil moisture
Treatment	Control							
	Compost	ß = 0.60 t(99) = 0.44 p = 0.66	ß = 205 t(99) = 1.3 p = 0.21	ß = 2.6 t(99) = 0.43 p = 0.67	ß = -37 t(99) = -0.73 p = 0.47	ß = 60 t(99) = 2.2 p = 0.029	ß = 633 t(99) = 1.5 p = 0.13	ß = -0.088 t(550) = -1.6 p = 0.10
	Chicken manure	ß = 4.3 t(99) = 3.1 p = 0.0029	ß = 405 t(99) = 2.4 p = 0.017	ß = 22 t(99) = 3.5 p < 0.001	ß = 152 t(99) = 3.0 p = 0.0038	ß = -15 t(99) = -0.56 p = 0.58	ß = 519 t(99) = 1.2 p = 0.22	ß = -0.16 t(550) = -3.1 p = 0.0023
	NPK fertiliser	ß = 0.82 t(99) = 0.57 p = 0.57	ß = 302 t(99) = 1.8 p = 0.080	ß = 37 t(99) = 5.9 p < 0.001	ß = 189 t(99) = 3.6 p < 0.001	ß = 18 t(99) = 0.65 p = 0.52	ß = 756 t(99) = 1.8 p = 0.080	ß = -0.24 t(550) = -4.5 p < 0.001
Garden type	New							
	Fallowed	ß = 2.1 t(27) = 1.2 p = 0.24	ß = 605 t(13) = 2.1 p = 0.058	ß = 1.3 t(20) = 0.15 p = 0.88	ß = -172 t(11) = -1.5 p = 0.16	ß = -139 t(11) = -2.4 p = 0.034	ß = -48 t(11) = -0.051 p = 0.96	ß = -0.12 t(550) = -2.3 p = 0.023
Harvest	Harvest 1							
	Harvest 2	ß = 2.3 t(99) = 2.7 p = 0.0080	ß = -278 t(99) = -2.8 p = 0.0067	ß = 7.9 t(99) = 2.1 p = 0.037	ß = -24 t(99) = -0.79 p = 0.43	ß = 41 t(99) = 2.5 p = 0.015	ß = -136 t(99) = -0.54 p = 0.59	ß = 0.17 t(550) = 5.0 p < 0.001

	Harvest 3	ß = -0.53 t(99) = -0.61 p = 0.54	ß = -190 t(99) = -1.9 p = 0.067	ß = 7.9 t(99) = 2.1 p = 0.042	ß = 42 t(99) = 1.3 p = 0.18	ß = 1.7 t(99) = 0.098 p = 0.92	ß = 183 t(99) = 0.71 p = 0.48	ß = -0.26 t(550) = -7.5 p < 0.001
Treatment * Garden type	Control : New							
	Compost : Fallowed	ß = -0.70 t(99) = -0.36 p = 0.72	ß = -120 t(99) = -0.52 p = 0.60	ß = -5.9 t(99) = -0.68 p = 0.50	ß = 114 t(99) = 1.6 p = 0.11	ß = 38 t(99) = 0.98 p = 0.33	ß = -779 t(99) = -1.3 p = 0.18	ß = -0.094 t(550) = -1.2 p = 0.23
	Chicken manure : Fallowed	ß = -2.0 t(99) = -1.0 p = 0.30	ß = -474 t(99) = -2.0 p = 0.045	ß = -8.3 t(99) = -0.95 p = 0.34	ß = -81 t(99) = -1.1 p = 0.26	ß = -7.2 t(99) = -0.19 p = 0.85	ß = -150 t(99) = -0.26 p = 0.80	ß = 0.096 t(550) = 1.3 p = 0.20
	NPK fertiliser : Fallowed	ß = -0.67 t(99) = -0.34 p = 0.74	ß = -383 t(99) = -1.6 p = 0.11	ß = -27 t(99) = -3.0 p = 0.0033	ß = -45 t(99) = -0.63 p = 0.53	ß = 12 t(99) = 0.31 p = 0.75	ß = -634 t(99) = -1.1 p = 0.29	ß = 0.020 t(550) = 0.27 p = 0.79

B - Table 10 | Model results from the models with an interaction between treatment and garden type on plant nutrients at harvests 1, 2 and 3. Reference levels are given in grey shading for each variable.

		Plant total N	**Plant total P**	**Plant total K**	**Plant total C**
Treatment	Control				
	Compost	ß = 240 t(102) = 0.17 p = 0.86	ß = 371 t(102) = 1.1 p = 0.26	ß = 2904 t(102) = 1.9 p = 0.055	ß = -2741 t(102) = -0.67 p = 0.51
	Chicken manure	ß = 820 t(102) = 0.58 p = 0.56	ß = 578 t(102) = 1.8 p = 0.079	ß = 2333 t(102) = 1.6 p = 0.12	ß = -1639 t(102) = -0.40 p = 0.69
	NPK fertiliser	ß = -1040 t(102) = -0.74 p = 0.46	ß = 303 t(102) = 0.93 p = 0.35	ß = 2089 t(102) = 1.4 p = 0.17	ß = 821 t(102) = 0.20 p = 0.84
Garden type	New				
	Fallowed	ß = -5144 t(23) = -2.7 p = 0.012	ß = -1128 t(15) = -2.1 p = 0.057	ß = -1363 t(17) = -0.60 p = 0.56	ß = 5992 t(16) = 0.92 p = 0.37
Harvest	Harvest 1				
	Harvest 2	ß = -1338 t(102) = -1.6 p = 0.12	ß = 1.8 t(102) = 0.009 p = 0.99	ß = 7003 t(102) = 7.6 p < 0.001	ß = 11358 t(102) = 4.5 p < 0.001

	Harvest 3	ß = -4314 t(102) = -5.0 $p < 0.001$	ß = -1946 t(102) = -9.8 $p < 0.001$	ß = -6950 t(102) = -7.6 $p < 0.001$	ß = 17407 t(102) = 6.9 $p < 0.001$
Treatment * Garden type	Control : New				
	Compost : Fallowed	ß = 952 t(102) = 0.48 p = 0.63	ß = -269 t(102) = -0.58 p = 0.56	ß = -2858 t(102) = -1.4 p = 0.18	ß = 4853 t(102) = 0.84 p = 0.41
	Chicken manure : Fallowed	ß = 525 t(102) = 0.26 p = 0.79	ß = 325 t(102) = 0.71 p = 0.48	ß = -2829 t(102) = -1.3 p = 0.18	ß = 4101 t(102) = 0.71 p = 0.48
	NPK fertiliser : Fallowed	ß = 1700 t(102) = 0.85 p = 0.40	ß = -260 t(102) = -0.57 p = 0.57	ß = -3128 t(102) = -1.5 p = 0.14	ß = -268 t(102) = -0.046 p = 0.96

B - Table 11 | Model results from the models on tuber nutrients at harvests 1, 2 and 3. Reference levels are given in grey shading for each variable.

		Tuber total N	Tuber total P	Tuber total K	Tuber total C
Treatment	Control				
	Compost	ß = 128 t(6) = 0.16 p = 0.88	ß = 93 t(6) = 0.40 p = 0.70	ß = 322 t(6) = 0.18 p = 0.87	ß = -1543 t(6) = -0.79 p = 0.46
	Chicken manure	ß = 163 t(6) = 0.20 p = 0.85	ß = 346 t(6) = 1.5 p = 0.19	ß = 414 t(6) = 0.23 p = 0.83	ß = -4375 t(6) = -2.2 p = 0.067
	NPK fertiliser	ß = -524 t(6) = -0.64 p = 0.55	ß = -227 t(6) = -0.97 p = 0.37	ß = -3021 t(6) = -1.7 p = 0.15	ß = -1359 t(6) = -0.69 p = 0.51
Harvest	Harvest 1				
	Harvest 2	ß = -3042 t(6) = -4.3 p = 0.0053	ß = -870 t(6) = -4.3 p = 0.0050	ß = -817 t(6) = -0.52 p = 0.62	ß = 11246 t(6) = 6.6 p < 0.001
	Harvest 3	ß = -1010 t(6) = -1.4 p = 0.21	ß = -959 t(6) = -4.8 p = 0.0031	ß = -4877 t(6) = -3.1 p = 0.021	ß = 25092 t(6) = 15 p < 0.001

B - Table 12 | Model results from the models on leaf yield, vine yield, tuber yield and tuber quality in new gardens and fallowed gardens separately at harvests 1, 2 and 3. Reference levels are given in grey shading for each variable.

		Leaf yield	Vine yield	Tuber yield	Weight per tuber	Number of tubers per mound
				New gardens		
Treatment	Control					
	Compost	ß = -0.30 t(461) = -4.7 $p < 0.001$	ß = -0.21 t(462) = -3.5 $p < 0.001$	ß = -0.26 t(479) = -2.7 $p = 0.0074$	ß = -0.19 t(2737) = -3.4 $p < 0.001$	ß = -0.011 t(485) = -0.17 $p = 0.86$
	Chicken manure	ß = 0.19 t(461) = 3.1 $p = 0.0018$	ß = 0.26 t(462) = 4.6 $p < 0.001$	ß = -0.0079 t(479) = -0.088 $p = 0.93$	ß = 0.020 t(2737) = 0.40 $p = 0.69$	ß = -0.054 t(485) = -0.91 $p = 0.36$
	NPK fertiliser	ß = 0.19 t(461) = 3.2 $p = 0.0017$	ß = 0.34 t(462) = 6.0 $p < 0.001$	ß = 0.33 t(479) = 3.7 $p < 0.001$	ß = 0.066 t(2737) = 1.4 $p = 0.16$	ß = 0.29 t(485) = 5.4 $p < 0.001$
Tuber type	Red					
	Mix	ß = -0.0023 t(461) = -0.025 $p = 0.98$	ß = -0.15 t(462) = -1.7 $p = 0.093$	ß = -0.16 t(479) = -1.2 $p = 0.22$	ß = 0.045 t(2737) = 0.66 $p = 0.51$	ß = -0.15 t(485) = -1.9 $p = 0.055$

Harvest	Harvest 1					
	Harvest 2	ß = 0.16	ß = -0.16	ß = 0.021	ß = 0.39	ß = -0.25
		t(461) = 2.7	t(462) = -3.0	t(479) = 0.25	t(2737) = 8.7	t(485) = -4.9
		p = 0.0064	p = 0.0027	p = 0.80	p < 0.001	p < 0.001
	Harvest 3	ß = -0.048	ß = -0.34	ß = -0.21	ß = 0.33	ß = -0.42
		t(461) = -0.82	t(462) = -6.3	t(479) = -2.5	t(2737) = 7.0	t(485) = -7.7
		p = 0.41	p < 0.001	p = 0.013	p < 0.001	p < 0.001
Fallowed gardens						
Treatment	Control					
	Compost	ß = -0.056	ß = -0.044	ß = 0.13	ß = -0.0018	ß = 0.20
		t(465) = -0.89	t(463) = -0.81	t(471) = 1.6	t(3039) = -0.034	t(481) = 3.3
		p = 0.37	p = 0.42	p = 0.12	p = 0.97	p < 0.001
	Chicken manure	ß = -0.014	ß = 0.19	ß = 0.27	ß = 0.056	ß = 0.22
		t(465) = -0.25	t(463) = 3.9	t(471) = 3.8	t(3039) = 1.2	t(481) = 4.1
		p = 0.81	p < 0.001	p < 0.001	p = 0.24	p < 0.001
	NPK fertiliser	ß = 0.061	ß = 0.36	ß = 0.44	ß = 0.056	ß = 0.40
		t(465) = 1.1	t(463) = 7.4	t(471) = 6.1	t(3039) = 1.2	t(481) = 7.6
		p = 0.28	p < 0.001	p < 0.001	p = 0.22	p < 0.001
Tuber type	Red					
	Mix	ß = 0.34	ß = 0.19	ß = -0.20	ß = -0.093	ß = -0.14
		t(465) = 3.2	t(463) = 2.1	t(471) = -1.5	t(3039) = -1.1	t(481) = -1.4
		p = 0.0015	p = 0.039	p = 0.14	p = 0.28	p = 0.15

Harvest	Harvest 1					
	Harvest 2	ß = 0.014 t(465) = 0.25 p = 0.80	ß = -0.055 t(463) = -1.2 p = 0.25	ß = 0.15 t(471) = 2.2 p = 0.031	ß = 0.26 t(3039) = 6.3 p < 0.001	ß = -0.11 t(481) = -2.3 p = 0.021
	Harvest 3	ß = -0.23 t(465) = -4.3 p < 0.001	ß = -0.079 t(463) = -1.7 p = 0.090	ß = -0.30 t(471) = -4.4 p < 0.001	ß = 0.050 t(3039) = 1.2 p = 0.24	ß = -0.34 t(481) = -6.9 p < 0.001

B - Table 13 | Model results from the models with an interaction between treatment and garden type on leaf yield, vine yield, tuber yield and tuber quality at harvests 1, 2 and 3. Reference levels are given in grey shading for each variable.

		Leaf yield	**Vine yield**	**Tuber yield**	**Weight per tuber**	**Number of tubers per mound**	**Tuber quality**
Treatment	Control						
	Compost	ß = -0.29 t(929) = -4.6 p < 0.001	ß = -0.22 t(928) = -3.9 p < 0.001	ß = -0.27 t(955) = -3.1 p = 0.0022	ß = -0.18 t(5778) = -3.2 p = 0.0014	ß = -0.015 t(968) = -0.23 p = 0.82	ß = -0.45 t(5340) = -2.6 p = 0.011
	Chicken manure	ß = 0.19 t(929) = 3.1 p = 0.0018	ß = 0.25 t(928) = 4.5 p < 0.001	ß = -0.011 t(955) = -0.13 p = 0.89	ß = 0.024 t(5778) = 0.46 p = 0.64	ß = -0.056 t(968) = -0.95 p = 0.34	ß = -0.073 t(5340) = -0.44 p = 0.66
	NPK fertiliser	ß = 0.18 t(929) = 3.1 p = 0.0020	ß = 0.33 t(928) = 6.1 p < 0.001	ß = 0.32 t(955) = 4.0 p < 0.001	ß = 0.059 t(5778) = 1.3 p = 0.21	ß = 0.28 t(968) = 5.4 p < 0.001	ß = -0.072 t(5340) = -0.46 p = 0.65
Garden type	New						
	Fallowed	ß = 0.095 t(929) = 1.6 p = 0.11	ß = -0.058 t(928) = -1.1 p = 0.27	ß = 0.11 t(955) = 1.3 p = 0.18	ß = 0.12 t(5778) = 2.4 p = 0.017	ß = -0.013 t(968) = -0.23 p = 0.82	ß = 0.49 t(5340) = 1.9 p = 0.054
Tuber type	Red						
	Mix	ß = 0.14 t(929) = 2.0 p = 0.046	ß = 0.0039 t(928) = 0.062 p = 0.95	ß = -0.18 t(955) = -1.9 p = 0.053	ß = -0.031 t(5778) = -0.59 p = 0.55	ß = -0.13 t(968) = -2.1 p = 0.036	ß = -0.26 t(5340) = -2.0 p = 0.041

Harvest	Harvest 1						
	Harvest 2	ß = 0.079 t(929) = 2.0 p = 0.051	ß = -0.11 t(928) = -3.0 p = 0.0025	ß = 0.086 t(955) = 1.6 p = 0.11	ß = 0.31 t(5778) = 10 p < 0.001	ß = -0.17 t(968) = -4.9 p < 0.001	ß = 0.26 t(5340) = 3.7 p < 0.001
	Harvest 3	ß = -0.15 t(929) = -3.7 p < 0.001	ß = -0.21 t(928) = -5.8 p < 0.001	ß = -0.26 t(955) = -4.8 p < 0.001	ß = 0.17 t(5778) = 5.3 p < 0.001	ß = -0.37 t(968) = -10 p < 0.001	ß = -0.19 t(5340) = -2.5 p = 0.012
Treatment * Garden type	Control : New						
	Compost : Fallowed	ß = 0.23 t(929) = 2.5 p = 0.013	ß = 0.19 t(928) = 2.4 p = 0.019	ß = 0.40 t(955) = 3.2 p = 0.0016	ß = 0.15 t(5778) = 1.9 p = 0.056	ß = 0.22 t(968) = 2.5 p = 0.013	ß = 0.12 t(5340) = 0.50 p = 0.62
	Chicken manure : Fallowed	ß = -0.20 t(929) = -2.3 p = 0.020	ß = -0.050 t(928) = -0.66 p = 0.51	ß = 0.28 t(955) = 2.5 p = 0.014	ß = 0.031 t(5778) = 0.44 p = 0.66	ß = 0.28 t(968) = 3.5 p < 0.001	ß = -0.29 t(5340) = -1.2 p = 0.21
	NPK fertiliser : Fallowed	ß = -0.13 t(929) = -1.5 p = 0.13	ß = 0.034 t(928) = 0.45 p = 0.66	ß = 0.12 t(955) = 1.0 p = 0.31	ß = 0.00041 t(5778) = 0.006 p = 1.0	ß = 0.11 t(968) = 1.5 p = 0.13	ß = -0.29 t(5340) = -1.3 p = 0.18

B - Table 14 | Model results from the taste test. Reference levels are given in grey shading for each variable.

	Taste rank
Control	
Compost	ß = -0.30 z(196) = -0.82 p = 0.41
Chicken manure	ß = -0.97 z(196) = -2.7 p = 0.0074
NPK fertiliser	ß = -0.41 z(196) = -1.1 p = 0.26
Harvest 1	
Harvest 2	ß = -0.35 z(196) = -1.1 p = 0.27
Harvest 3	ß = -0.36 z(196) = -1.2 p = 0.23

B - Table 15 | Model results from the SEM. Reference levels are given in grey shading for each variable.

	Soil available N	Soil available P	Soil available K	Soil moisture	Tuber yield
Control					
Compost	ß = 0.26 df = 101 p = 0.79	ß = -0.30 df = 101 p = 0.95	ß = 78 df = 101 p < 0.001	ß = -2.9 df = 100 p = 0.010	ß = -0.37 df = 97 p = 0.010
Chicken manure	ß = 3.3 df = 101 p = 0.0012	ß = 18 df = 101 p < 0.001	ß = -19 df = 101 p = 0.32	ß = -1.5 df = 100 p = 0.19	ß = -0.099 df = 97 p = 0.50
NPK fertiliser	ß = 0.64 df = 101 p = 0.52	ß = 24 df = 101 p < 0.001	ß = 25 df = 101 p = 0.20	ß = -3.3 df = 100 p = 0.010	ß = 0.11 df = 97 p = 0.47
New garden					
Fallowed garden	ß = 1.2 df = 8 p = 0.38	ß = -8.7 df = 8 p = 0.22	ß = -128 df = 8 p = 0.040	ß = -2.0 df = 8 p = 0.59	ß = 0.41 df = 8 p = 0.21
Harvest 1					
Harvest 2	ß = 2.4 df = 101 p = 0.0053	ß = 8.2 df = 101 p = 0.039	ß = 41 df = 101 p = 0.014	ß = 3.7 df = 100 p < 0.001	ß = 0.14 df = 97 p = 0.26
Harvest 3	ß = -0.54 df = 101 p = 0.53	ß = 7.4 df = 101 p = 0.065	ß = 1.4 df = 101 p = 0.93	ß = -5.1 df = 100 p < 0.001	ß = -0.59 df = 97 p < 0.001
Total plant biomass				ß = -0.0033 df = 100 p = 0.031	Correlated ß = 0.34 df = 116 p < 0.001
Soil available N					ß = 0.032 df = 97 p = 0.019
Soil available P					ß = -0.0020 df = 97 p = 0.49

Soil available K	ß = 0.0005 df = 97 p = 0.41
Soil moisture	ß = -0.053 df = 97 $p < 0.001$

B - Table 16 | Financial feasibility of using NPK fertiliser.

Financial profitability when not using any type of fertiliser

- When not using any type of fertiliser farmers in Ohu harvest, on average, 4.8 sweet potato tubers per mound (Fig. 4.5).
- There is a 62% chance that the tuber is fit for human consumption and can be marketed, so farmers can sell 2.9 tubers per mound.
- Farmers in Ohu tend on average 55 sweet potato mounds, from which they can harvest approximately three times a year, depending on the variety of sweet potato planted.
- The average price of a sweet potato on the Madang market is 0.20 per tuber.
- So, farmers in Ohu can earn 0.59 PGK[2] per sweet potato mound or 97 PGK[3] per year.

Costs of NPK fertiliser

- The price of NPK fertiliser in Madang town is 26.50 PGK for 5 kg.
- If you apply 16.3 grams of fertiliser per mound (as done in the experiment), the cost of NPK fertiliser comes to 0.086 PGK per mound

Profit of NPK fertiliser

- On average, you harvest an additional two tubers per mound when applying NPK fertiliser compared to the control condition (Fig. 4.5).
- There is a 62% chance that the tuber is fit for human consumption and can be marketed, so when using NPK fertiliser you harvest, on average, 1.2 more tubers that can be sold on the market.
- The average price of a sweet potato on the Madang market is 0.20 per tuber.
- The maximum profit you can make by using NPK fertiliser comes to 0.25 PGK per mound.

Balance

- On balance, farmers in Ohu can earn a maximum of 0.16 PGK more per mound when using NPK fertiliser.
- Farmers in Ohu tend on average 55 sweet potato mounds, from which they can harvest approximately three times a year, depending on the variety of sweet potato planted.
- Thus, in a year farmers in Ohu can make a maximum additional profit of 26 PGK per year if they use NPK fertiliser. This is a 27% increase in income from not using any fertiliser.

[2] In January 2021, 1 PGK converted to 0.21 GBP.
[3] To put this amount in its context, the price of one kilo of rice in PNG currently ranges between 3.50 – 5 PKG.

Appendix C – Supplementary material for Chapter 5

1. Stochastic actor-oriented model simulations

I used stochastic actor-oriented modelling to simulate the observed evolution of the network and farming behaviour, while accounting for normative network processes and individual characteristics. The stochastic actor-oriented model (SAOM) is based on the assumption that the network evolves as a stochastic process that is driven by its actors. The model is conditioned on the first observation. Consequently, the analysis does not make inferences about the determinants of the network structure at the first time point, but models the change between two observed periods. Between these two observation moments, actors receive chances in a random order to change the ties in their network. They can create new ties, delete existing ties or do nothing, a process that is also stochastic. An actor can also choose to increase, decrease or maintain its level of behaviour. Only one actor acts at a time, and coordination between changes in the network and behaviour is not allowed. SAOMs allow you to specify the exact ways in which current network structure and covariates may affect the network or behaviour. These are called effects. Examples of effects include the 'outdegree effect' which represents the total number of ties in the network or the 'reciprocity effect' which represents the number of reciprocated ties. The strength of each effect in determining the network and behaviour dynamics is estimated from longitudinal data using a simulation-based approach (Ripley *et al.*, 2019). Separate utility functions are evaluated for the actor's network and behaviour choices. It is assumed that each actor is most likely to maximise his or her personal 'satisfaction'. This 'satisfaction' is captured by a function, which is usually taken to be linear combinations of effects which depend on the network structure and the endogenous characteristics of the actors. The goal of the simulation is to estimate a parameter for each effect that is specified in the model. This parameter can be interpreted in a similar way to parameters of multinomial logistic regression models, meaning that it represents the log-probabilities of changes among which the actors can choose. Another often used approach for the statistical analyses of social network generation is the exponential random graph model (ERGM) (Lusher, Koskinen, & Robins, 2013). Here I aim to test a specific actor-based theory, which is more directly tested and modelled with SAOM compared to ERGM, and thus I opted for the SAOM in this paper (Block, Stadtfeld, & Snijders, 2019).

Analyses for the SAOM were carried out by the RSiena package version 4 in R (Ripley *et al.*, 2019). The reported result is taken from a run in which all 't-ratios for deviations from targets' were between -0.1 and 0.1 in absolute value and the 'overall maximum convergence ratio' lower than 0.25, indicating excellent convergence of the algorithm (Ripley *et al.*, 2019). I assessed the model's goodness of fit by comparing observed values with simulated values for in-degree, out-degree, geodesic distance (quantifying the overall connectivity of the network) and triadic census (quantifying the distribution of all combinations of directed triangles in the network). The differences were assessed by combining the auxiliary statistics using the Mahalanobis distance, and based on this employing a Monte Carlo test to compute frequentist p-values (Lospinoso, 2012). The null hypothesis is that these distributions are the same, making its rejection undesirable. For my model all p-values were above 0.1, which indicates an acceptable fit between the simulations and observed networks.

References

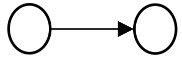
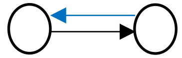
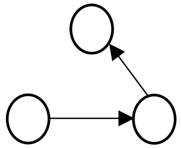
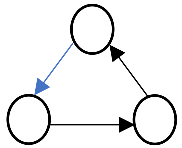
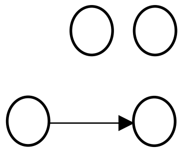
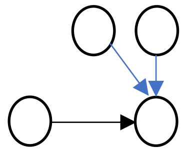
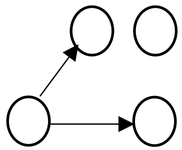
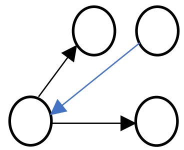
Block, P., Stadtfeld, C. and Snijders, T. A. B. (2019) 'Forms of dependence: comparing SAOMs and ERGMs from basic principles', *Sociological Methods and Research*, 48(1), pp. 202–239. doi: 10.1177/0049124116672680.

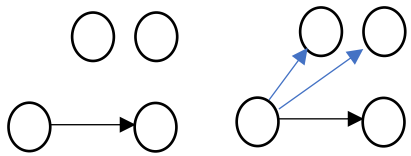
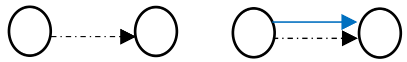
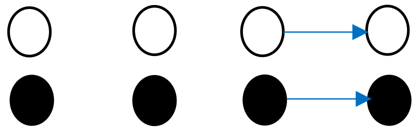
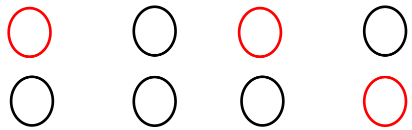
Lospinoso, J. (2012) *Statistical models for social network dynamics*. University of Oxford.

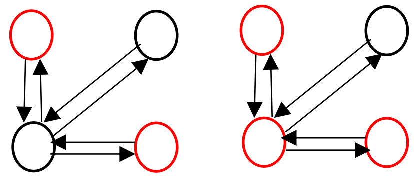
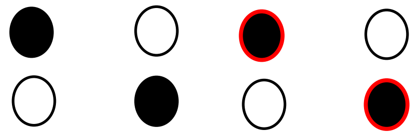
Lusher, D., Koskinen, J. and Robins, G. (2013) *Exponential Random Graph Models for social networks: theory, methods and applications*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511894701.

Ripley, R. M., Snijders, T. A. B., Boda, Z., Vörös, A. and Preciado, P. (2019) *Manual for RSIENA version 4.0*, *University of Oxford, Department of Statistics, Nuffield College*.

C - Table 1 | Overview and explanation of the effects included in the RSiena models.

Effect name	RSiena effect name	Explanation	Graphical representation	
	Structural network effects		*Time 1*	*Time 2*
Outdegree	Outdegree (density)	This is the basic tendency for an actor to have ties at all. Its parameter can be regarded as the balance of benefits and costs of an arbitrary tie. In most cases the parameter is negative, meaning that for creating a tie to an arbitrary other actor the costs will usually outweigh the benefits.		
Reciprocity	Reciprocity (recip)	This is the tendency to reciprocate received nominations. It is a basic feature of most social networks and the parameter value usually ranges between 1 and 2.		
Clustering	Transitive triplets (transTrip)	Defined by the number of transitive patterns in the relations of an actor. A transitive pattern occurs when actor A is tied to actor B and C, while actor C is also tied to actor B. If this effect is positive it means that ties that create more transitive triads have a greater likelihood.		
In-degree related popularity	Indegree-popularity (inPop)	Measure of in-degree related popularity, defined by the sum of the in-degrees nominations of the others to whom an actor is tied. A positive in-degree popularity effect implies that nodes with higher in-degrees are more attractive for others to send a tie to.		
Out-degree related popularity	Outdegree-popularity (outPop)	Measure of the out-degree related popularity of an actor, defined by the sum of the out-degrees of the others to whom an actor is tied. A positive out-degree related popularity effect will cause actors who have a high out-degree to attract incoming nominations, thus increasing the association between in-degrees and out-degrees.		

Out-degree related activity	Out-degree activity (outAct)	Measure of out-degree activity of an actor, defined by the number of out-degree squared. When this effect is positive, nodes with higher out-degrees will have an extra propensity to form ties to others.		
Effect of an individual's attribute(s) on the network			*Time 1*	*Time 2*
Friendship	*Attribute* main effect (X)	Tendency to send a nomination to actors with whom one has another type of relation.		
Effect on ego	*Attribute* ego (egoX)	This measure indicates whether for an actor attribute *V*, actors with higher levels of the attribute nominate a higher number of people, and hence have a higher out-degree.		
Effect on alter	*Attribute* alter (altX)	This measure indicates whether actors with higher *V* values receive more nominations from others, and thus have higher in-degrees.		
Effect of same covariate	Same *attribute* (sameX)	It is defined by the number of ties of an actor to another actor who has the exact same value on the attribute.		
Covariate-related popularity	*Attribute* squared alter (altSqX)	Square of altX.		
Covariate-related activity	*Attribute* squared ego (egoSqX)	Square of egoX.		
Covariate-related squared difference	*Attribute* diff. squared (diffSqX)	Square of altX minus egoX.		
Effect of the network and an individual's attribute on behaviour diffusion			*Time 1*	*Time 2*
Overall linear growth	Behaviour linear shape (linear)	This effect defines the balance between the probabilities of a dependent behaviour variable going up and going down.		

Effect of network	*Behaviour* total rec. alters (totRecAlt, name = *'behaviour'*, interaction1 = *'network'*)	Allows you to study the effect of the network on the uptake of a behaviour. In this case I investigated whether the behaviour of an actor was affected by the sum of behaviour of his reciprocated alters.	
Effect of attribute	*Behaviour* effect from *attribute* (name = '*behaviour'*, effFrom, interaction1 = *'attribute'*)	Allows you to study the direct effect of an actor attribute on a dependent behaviour variable.	

C - Table 2 | Overview of the effects included in the full RSiena model (left) and the network only RSiena model (right).

Effect name	RSiena effect name	Full model	Network only model
	Structural network effects		
Outdegree		✓	✓
Reciprocity	Recip	✓	✓
Clustering	transTrip	✓	✓
In-degree related popularity	inPop	✓	✓
Out-degree related popularity	outPop	✓	✓
Out-degree related activity	outAct	✓	✓
	Effect of an individual's attribute(s) on the network		
Distance	X	✓	✓
Clan	sameX	✓	✓
Gender	egoX	✓	✓
	altX	✓	✓
	sameX	✓	✓
Age	egoX	✓	✓
	altX	✓	✓
	egoSqX	✓	✓
	altSqX	✓	✓
	diffSqX	✓	✓
Project	egoX	✓	
	altX	✓	
	sameX	✓	

Project – Garden owner	egoX		✓
	altX		✓
	sameX		✓
Project – Research assistant	egoX		✓
	altX		✓
	sameX		✓
Effect of an individual's behaviour on the network			
Total researched	egoX	✓	
	altX	✓	
	sameX	✓	
Mulching	egoX	✓	
	altX	✓	
	sameX	✓	
Effect of the network and an individual's attribute on behaviour diffusion			
Total researched	linear	✓	
	totRecAlt	✓	
	effFrom Project	✓	
Mulching	linear	✓	
	totRecAlt	✓	
	effFrom Project	✓	
Variety	effFrom Project	✓	
Learned	effFrom Project	✓	

C - Table 3 | Dynamics of the network and the practice of using any of the researched techniques, mulching, planting the project's variety of sweet potato and having learned something from the project. (+)/(-) = p < 0.1, +/- = p < 0.05, ++/-- = p < 0.01, +++/--- = p < 0.001, with + indicating a positive effect and - a negative effect. The estimate shows the change between the two surveys in the effect of the variable. I did not find evidence that the social network influenced the use of the tested farming practices, or that these practices influenced the social network. Farmers did not adapt their practices based on what those with whom they have a reciprocal relationship do, both for practising any of the researched techniques or for mulching, as indicated by the non-significant network effects on these behaviours. There was also no tendency for farmers who used any of the researched techniques or practiced mulching to seek more advice from others, to be asked more for advice by other farmers or to speak among themselves, as shown by the non-significant ego, alter and same effects for behaviours.

	Description	Estimate	Standard error	p-level	Confidence interval	
	Structural network effects				*5%*	*95%*
Outdegree	Overall information-seeking activity	-5.4455	6.0312		-17.3	6.38
Reciprocity	Interchange information	1.8031	0.5890	++	0.649	2.96
Transitive ties	Clustering of information network	0.7820	0.3793	+	0.0386	1.53
In-degree popularity	Tendency for farmers with high in-degrees to attract more ties	-0.0668	0.1691		-0.398	0.265
Out-degree popularity	Tendency for farmers with high out-degrees to attract more ties	-0.2706	0.3258		-0.909	0.368
Out-degree activity	Tendency for farmers with high out-degrees to form more out-going ties	-0.2372	0.3869		-0.996	0.521
	Effect of an individual's attribute(s) on the network				*5%*	*95%*
Distance	Geographical proximity influences tie formation	-0.0027	0.0015	(-)	-0.00564	0.00024
Same clan	Preference for advisors from the same clan	0.9458	0.5742	(+)	-0.180	2.07
Gender						
• Ego	Tendency for women to seek more information	0.3674	0.6113		-0.831	1.57
• Alter	Preference for female advisors	-0.6394	0.5324		-1.68	0.404
• Same	Preference for advisors from the same gender	0.5576	0.4140		-0.254	1.37

Age						
• Ego	Tendency for older people to seek more information	-0.0218	0.0270		-0.0747	0.0311
• Alter	Preference for older advisors	0.0045	0.0162		-0.0272	0.0363
• Ego squared		0.0008	0.0013		-0.00175	0.00335
• Alter squared		-0.0005	0.0010		-0.00246	0.00146
• Alter minus ego squared		0.0002	0.0005		-0.00078	0.00118
Project						
• Ego	Tendency for project participants to seek more information	0.5346	0.7986		-1.03	2.10
• Alter	Preference for advisors who take part in the project	1.0655	0.4907	+	0.104	2.03
• Same	Preference of non-participants toward non-participants and participants toward participants	0.4742	0.3380		-0.188	1.14
	Effect of an individual's behaviour on the network				*5%*	*95%*
Total researched						
• Ego	Tendency for farmers who use any of the researched techniques to seek more information	1.5345	2.9507		-4.25	7.32
• Alter	Preference for advisors who use any of the researched techniques	1.3855	4.8392		-8.10	10.9
• Same	Preference for advisors with the same practices	3.0459	7.0881		-10.8	16.9
Mulching						
• Ego	Tendency for farmers who use mulching to seek more information	-0.8667	1.5929		-3.99	2.26
• Alter	Preference for advisors who use mulching	-0.9350	1.0097		-2.91	1.04
• Same	Preference for advisors with the same practices	0.2190	1.0228		-1.79	2.22

	Effect of the network and an individual's attribute on behaviour diffusion				*5%*	*95%*
Total researched						
• Linear	Baseline increase in using any of the researched techniques	-0.1884	0.4812		-1.13	0.755
• Effect of network	Tendency of people to follow the behaviour of their reciprocated alters	0.2513	1.5573		-2.80	3.30
• Effect of project	Tendency of project participants compared to non-participants to use any of the researched techniques	-0.8019	0.7877		-2.35	0.742
Mulching						
• Linear	Baseline increase in using mulching	2.3412	0.9570	+	0.465	4.22
• Effect of network	Tendency of people to follow the behaviour of their reciprocated alters	-1.0034	5.7758		-12.3	10.3
• Effect of project	Tendency of project participants compared to non-participants to use mulching	-0.2971	1.4479		-3.13	2.54
Sweet potato variety						
• Effect of project	Tendency of project participants compared to non-participants to plant the project's sweet potato variety	3.4725	2.0186	(+)	-0.484	7.43
Learned						
• Effect of project	Tendency of project participants compared to non-participants to have learned from the project	6.0191	1.2585	+++	3.55	8.49
	Goodness of fit					
In-degree distribution	Distribution of information-seeking activity among farmers			0.574		
Out-degree distribution	Distribution of popularity among advisors			0.733		
Geodesic distribution	Learning network connectivity			0.271		
Triad census	Learning network clustering			0.459		

C - Table 4 | Overview of the full results of the logistic regressions with household as a random effect for the use of food waste, mulch, planting the research project's specific variety of sweet potato and having learned from the project. Reference levels are given in grey shading for each variable.

		Food waste	Mulching	Sweet potato variety	Learned
Project	Non-participant				
	Project garden owner	ß = 1.7 z(106) = 1.8 p = 0.070	ß = 2.1 z(106) = 1.5 p = 0.14	Model did not converge	(All project garden owners had learned)
	Research assistant	ß = 0.40 z(106) = 0.42 p = 0.67	ß = 1.7 z(106) = 1.6 p = 0.099		ß = 4.9 z(43) = 2.3 p = 0.023
Time	Time 1				
	Time 2	ß = 1.8 z(106) = 2.7 p = 0.0079	ß = 1.7 z(106) = 2.2 p = 0.031		
Gender	Man				
	Woman	ß = -0.55 z(106) = -1.0 p = 0.30	ß = 2.5 z(106) = 3.1 p = 0.0017		ß = 1.3 z(43) = 1.2 p = 0.22

Project *	Non-participant : Time 1		
Time	Project garden owner : Time 2	ß = -1.4 z(106) = -1.2 p = 0.24	ß = -2.8 z(106) = -1.6 p = 0.11
	Research assistant : Time 2	ß = -1.8 z(106) = -1.6 p = 0.12	ß = -0.22 z(106) = -0.15 p = 0.89

C - Table 5 | Overview of the effects included in the logistic regressions for the use of food waste, mulch, planting the research project's specific variety of sweet potato and having learned from the project. Reference levels are given in grey shading for each variable.

		Food waste	**Mulching**	**Sweet potato variety**	**Learned**
Project	Non-participant				
	Project garden owner	✓	✓	✓	(All project garden owners had learned so left out)
	Research assistant	✓	✓	✓	✓
Time	Time 1				
	Time 2	✓	✓		
Gender	Man				
	Woman	✓	✓	✓	✓
Project * Time	Non-participant : Time 1				
	Garden owner : Time 2	✓	✓		
	Research assistant : Time 2	✓	✓		

C - Table 6 | Overview of the full results of the logistic regressions for the use of food waste, mulch, planting the research project's specific variety of sweet potato and having learned from the project. Reference levels are given in grey shading for each variable.

		Food waste	Mulching	Sweet potato variety	Learned
Project	Non-participant				
	Project garden owner	ß = 1.6 z(107) = 1.9 p = 0.054	ß = 1.7 z(107) = 1.5 p = 0.14	ß = 0.43 t(53) = 0.37 p = 0.71	(All project garden owners had learned)
	Research assistant	ß = 0.57 z(107) = 0.67 p = 0.51	ß = 1.4 z(107) = 1.8 p = 0.080	ß = 3.3 t(53) = 2.9 p = 0.0050	ß = 4.4 z(44) = 3.5 p < 0.001
Time	Time 1				
	Time 2	ß = 1.7 z(107) = 2.6 p = 0.0085	ß = 1.4 z(107) = 2.1 p = 0.038		
Gender	Man				
	Woman	ß = -0.41 z(107) = -0.89 p = 0.38	ß = 2.1 z(107) = 3.4 p < 0.001	ß = 2.2 t(53) = 2.1 p = 0.040	ß = 1.1 z(44) = 1.3 p = 0.21
Project * Time	Non-participant : Time 1				
	Project garden owner : Time 2	ß = -1.3 z(107) = -1.2 p = 0.25	ß = -2.3 z(107) = -1.5 p = 0.14		

Research assistant : Time 2	ß = -1.7	ß = -0.076
	z(107) = -1.5	z(107) = -0.054
	p = 0.13	p = 0.96

C - Table 7 | Dynamics of the network. (+)/(-) = p < 0.1, +/- = p < 0.05, ++/-- = p < 0.01, +++/--- = p < 0.001, with + indicating a positive effect and - a negative effect. The estimate shows the change between the two surveys in the effect of the variable.

	Description	**Estimate**	**Standard error**	**p-level**	**Confidence interval**	
	Structural network effects				*5%*	*95%*
Outdegree	Overall information-seeking activity	-2.3746	0.7073	---	-3.76	-0.988
Reciprocity	Mutual information exchange	1.7578	0.3358	+++	1.10	2.42
Transitive ties	Clustering of information network	0.6821	0.2078	++	0.275	1.09
In-degree popularity	Tendency for farmers with high in-degrees to attract more ties	-0.0707	0.1114		-0.289	0.148
Out-degree popularity	Tendency for farmers with high out-degrees to attract more ties	-0.2606	0.1765		-0.607	0.0853
Out-degree activity	Tendency for farmers with high out-degrees to form more out-going ties	-0.1493	0.0942		-0.334	0.0353
	Effect of an individual's attribute(s) on the network				*5%*	*95%*
Distance	Geographical proximity influences tie formation	-0.0020	0.0005	---	-0.00298	-0.00102
Same clan	Preference for advisors from the same clan	0.8106	0.3290	+	0.166	1.46
Gender with ♀ = 1						
• Ego	Tendency for women to seek more information	0.2510	0.3154		-0.367	0.869
• Alter	Preference for female advisors	-0.5416	0.2746	-	-1.08	-0.00338
• Same	Preference for advisors from the same gender	0.4663	0.2501	(+)	-0.0239	0.956
Age						
• Ego	Tendency for older people to seek more information	-0.0183	0.0131		-0.0440	0.00738
• Alter	Preference for older advisors	0.0066	0.0115		-0.0159	0.0291
• Ego squared	Non-linear ego effect of age	0.0004	0.0008		-0.00117	0.00197
• Alter squared	Non-linear alter effect of age	-0.0006	0.0007		-0.00197	0.000772

• Alter minus ego squared		0.0002	0.0003		-0.00039	0.000788
Project garden owner						
• Ego	Tendency for project garden owners to seek more information	-0.1309	0.4287		-0.971	0.709
• Alter	Preference for advisors who are project garden owners	0.2593	0.4260		-0.576	1.094
• Same	Preference of project garden owners toward project garden owners	-0.0936	0.4159		-0.909	0.722
Project research assistant						
• Ego	Tendency for research assistants to seek more information	0.4926	0.3689		-0.230	1.22
• Alter	Preference for advisors who are research assistants	0.8816	0.3349	++	0.225	1.54
• Same	Preference of research assistants toward research assistants	-0.2459	0.2491		-0.734	0.242
			Goodness of fit			
In-degree distribution	Distribution of the information-seeking activity among farmers			0.563		
Out-degree distribution	Distribution of popularity among advisors			0.742		
Geodesic distribution	Learning network connectivity			0.161		
Triad census	Learning network clustering			0.319		

Appendix D – Supplementary material for Chapter 6

D - Table 1 | Description of the sample.

		Group 1	Group 2	Group 3
Total number of people		8	8	8
Age	Younger (<40 years)	4	4	4
	Older (>40 years)	4	4	4
Gender (no. of ♀)	Men	4	4	4
	Women	4	4	4
Tribe - Clan (no. of people)		Tribe 1 - Clan 1: 8	Tribe 1 - Clan 2: 8	Tribe 2 - Clan 3: 1 Tribe 2 – Clan 4: 2 Tribe 2 – Clan 5: 3 Tribe 3 – Clan 6: 1 Tribe 3 – Clan 7: 1

D - Table 2 | Overview of the five capitals and their definitions, used here to categorise the photographed items. Adapted from Scoones (1998) and Carney (1998).

Capital	Definition
Natural	Natural resource stocks (e.g. soil, water and air) and flows of energy and material that produce goods and services.
Human	The skills, knowledge, physical ability, motivation and health needed to pursue your livelihood.
Social	Social resources (e.g. schools, businesses and families) upon which people draw when pursuing their livelihood.
Physical	Materials goods and fixed assets (e.g. tools, roads and buildings) which are generated by applying human productive activities to natural capital, and which contribute to provide a flow of goods and services.
Financial	Capital base (e.g. shares, bonds and cash) which are needed for the pursuit of a livelihood. Unlike the other capitals it has no real value in itself, but it is representative of natural, human, social or physical capital.

D - Table 3 | Overview of how each photographed resource was classified into the different categories of capitals, following Scoones (1998) and Carney (1998). Items in quotation marks indicate the Tok Pisin name used, as I was not aware of the common English name.

Item photographed	Classified as
Aibika	Natural capital
Aid post	Physical capital
'Aila' (*Inocarpus fagifera*)	Natural capital
Bamboo	Natural capital
Banana	Natural capital
Bandicoot trap	Physical capital
Bank card	Financial capital
Bean	Natural capital
Betel nut	Natural capital
Bible	Physical capital
Bilum	Physical capital
Boombox	Physical capital
Breadfruit	Natural capital
Cacao	Natural capital
Car	Physical capital
Cassava	Natural capital
Chicken	Natural capital
Coconut	Natural capital
Conservation project	Social capital
Cooking oil	Physical capital
Corn	Natural capital
Mustard	Natural capital
Drum	Physical capital
Fence	Physical capital
Fermentary	Physical capital
Fish pond	Natural capital
Forest	Natural capital
Garden	Natural capital
Garden food	Natural capital
Generator	Physical capital
House and kitchen	Physical capital
'Kanda' (*Flagellaria indica*)	Natural capital

'Kumu mosong' (*Ficus copiosa* Steud.)	Natural capital
Land	Natural capital
Malay apple tree	Natural capital
Mango	Natural capital
Mat	Physical capital
Mobile phone	Physical capital
Modern clothes	Physical capital
Pacific walnut (*Dracontomelon dao*)	Natural capital
Money	Financial capital
Okari nut	Natural capital
Palm species (*Hydriastele costata*)	Natural capital
Pandanus	Natural capital
Papaya	Natural capital
Pig	Natural capital
Pineapple	Natural capital
Pumpkin	Natural capital
Road	Physical capital
Sago	Natural capital
School	Social capital
Shop	Social capital
'Sis' (*Pengume edule*)	Natural capital
Solar panel and battery	Physical capital
Store food	Physical capital
Sweet potato	Natural capital
Taro	Natural capital
Chinese taro	Natural capital
Tomato	Natural capital
'Ton' (*Pometia pinnata*)	Natural capital
Tools	Physical capital
Traditional items	Physical capital
'Tulip' (*Gnetum gnemon* L.)	Natural capital
Vanilla	Natural capital
Water	Natural capital
Wooden utensils	Physical capital
Yam varieties	Natural capital

D - Table 4 | Overview of the five components of well-being and their definitions, used here to categorise the described meaning of photographed items. Adapted from Narayan *et al.* (2000).

Well-being component	Definition	Ill-being component	Definition
Basic material for a good life	Includes having access to food year-round, having adequate resources to make a living, and being able to gain a livelihood.	Material lack	Includes a lack of food, not having adequate resources to sustain a living, and being uncertain about employment.
Good health	Includes having good physical health, being able to dress and appear well, and living in a healthy physical environment.	Poor health	Including experiencing hunger, pain or discomfort, and often being exhausted.
Good social relations	Includes being able to marry and take care of children, being able to have self-respect and dignity, and have peaceful and good relations within the family, community and country.	Bad social relations	Includes being excluded by others or finding it necessary to self-exclude, being rejected and feeling lonely.
Security	Includes living in a peaceful, predictable and secure place, having access to justice, having security and support in old age, and being able to look forward to the future with confidence.	Vulnerability	Includes being exposed to mishaps, stresses and risks in the physical environment, society, economy or legal system, and being defenceless against damaging loss.
Freedom of choice and action	Includes being able to help others, and having the ability to make choices and have some control over what happens next.	Powerlessness	Includes being unable to control what happens, the inability to plan for the future and the imperative of focusing on the present.

D - Table 5 | Overview of how descriptions of the use of photographed resources were classified into the different categories well-being or ill-being, following Narayan *et al.* (2000).

Use of item	Classified as
Food	Basic material for a good life
Own consumption	Basic material for a good life
Drink	Basic material for a good life
Cook food	Basic material for a good life
Hunting	Basic material for a good life
Work tools	Basic material for a good life
Build house	Basic material for a good life
Use as bilum	Basic material for a good life
Firewood	Basic material for a good life
Make other assets	Basic material for a good life
Make farm	Basic material for a good life
Buy items	Basic material for a good life
Buy services	Freedom of choice and action
Storage	Basic material for a good life
Sell	Freedom of choice and action
Education	Freedom of choice and action
Job	Basic material for a good life
Provides services	Freedom of choice and action
Medicine	Good health
Harm health	Poor health
Harm assets	Material lack
Happiness	Good health
Clean	Good health
Social relations	Good social relations
Culture	Good social relations
Traditional dances	Good social relations
Safety	Security
Birth	Good health
Cover body	Good health
Fights	Bad social relations

Get drunk	Vulnerability
Marriage problems	Bad social relations
Steal	Vulnerability
Spoil environment	Poor health
Not work well	Poor health
Expensive	Material lack
Hard work	Material lack
Low yield	Material lack
Hot	Poor health
Communication	Good social relations
Transport	Basic material for a good life
Important for life	Basic material for a good life
Empower	Freedom of choice and action

D - Table 6 | Codes that emerged from the interviews and describe the main changes affecting the photographed resources, the drivers of these changes and possible adaptation strategies.

Theme	Codes emerging from the interviews
Changes	We live a tougher life
	We live a better life
	The future depends on God
	Not sure how the future will look like
	It is becoming sick
	Yields are low
	We look after it more
	We look after it less
	We use it less on a daily basis
	We use it more on a daily basis
	This resource will continue to be present
	Money is becoming more important
	We use it less for customary purposes
	We use it more for customary purposes
	We make a small farm
	We make no farm
	The resource is becoming short
	The quality of the resource is low
	There are fewer animals
	We change the way we make fences
	We change our diet
	We change the house we live in
	We change our life pattern
	We change to using modern materials
	We change the technique we are using
	We sell this more often
	We are now selling it, whereas before we wouldn't
	We sell this less often
	The price is going up
	The price is going down
	We engage in less customary purposes
	We are losing traditional knowledge
	We are losing traditional items

	We have more knowledge
	We are using modern medicines
	Babies are born in hospitals
	Services are coming to our community
	Sago is declining
	There are more law-and-order problems
	We hunt less
	We are spoiling our environment
Reasons for changes	We make more farms
	The forest is being lost
	People changed their attitude and became lazy
	The land is becoming short
	Soil quality is low
	The species is being overhunted
	We now use chemicals
	Insects are attacking more often
	The climate is changing
	The population is increasing
Adaptation strategies	We plant different species
	We need to buy items
	We need to save the resource
	Education is becoming more important

D - Table 7 | Outcomes of the Fisher's exact tests to determine whether capital and well/ill-being component changed over time. Row-wise post-hoc tests with Bonferroni correction are highlighted in grey were relevant.

		Time	
		Past to now	*Now to future*
Capital		$p = 0.0015$	$p < 0.001$
	Financial	$p = 0.99$	$p = 0.0020$
	Natural	$p = 0.046$	$p < 0.001$
	Physical	$p = 0.0068$	$p < 0.001$
	Social	$p = 1$	$p < 0.001$
Well/ill-being		$p = 0.006$	$p < 0.001$
	Basic material for a good life	$p = 1$	$p < 0.001$
	Material lack	$p = 1$	$p = 0.38$
	Good health	$p = 1$	$p = 0.67$
	Poor health	$p = 0.82$	$p < 0.001$
	Good social relations	$p = 0.35$	$p = 0.0016$
	Bad social relations	$p = 1$	$p < 0.001$
	Security	$p = 1$	$p = 0.19$
	Vulnerability	$p = 0.16$	$p < 0.001$
	Freedom of choice and action	$p = 0.061$	$p = 1$

D - Table 8 | Outcomes of the Fisher's exact tests to determine whether capital and well/ill-being components differed between younger vs. older people and women vs. men in the past, now or future. Row-wise post-hoc tests with Bonferroni correction are highlighted in grey where relevant.

			Group	
			Age (Younger, n = 12; Older, n = 12)	*Gender (Men, n = 12; Women, n = 12)*
Capital	Past		p = 0.39	p = 0.45
		Financial		
		Natural		
		Physical		
		Social		
	Now		p = 1.0	p = 0.19
		Financial		
		Natural		
		Physical		
		Social		
	Future		p = 0.43	p = 0.90
		Financial		
		Natural		
		Physical		
		Social		
Well/ill-being	Past		p = 0.035	p = 0.049
		Basic material for a good life	p = 1	p = 0.47
		Material lack	p = 0.98	p = 0.45
		Good health	p = 1	p = 1
		Poor health	p = 1	p = 1
		Good social relations	p = 1	p = 1
		Bad social relations	p = 0.84	p = 1
		Security	p = 0.49	p = 1
		Vulnerability		
		Freedom of choice and action	p = 1	p = 0.45
	Now		p = 0.45	p = 0.74
		Basic material for a good life		
		Material lack		

Good health		
Poor health		
Good social relations		
Bad social relations		
Security		
Vulnerability		
Freedom of choice and action		
Future	p = 0.50	p = 0.70
Basic material for a good life		
Material lack		
Good health		
Poor health		
Good social relations		
Bad social relations		
Security		
Vulnerability		
Freedom of choice and action		