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Evaluating ecosystem service trade offs with wind electricity production in Switzerland

Spatial planning of wind turbine locations using optimisation
software



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Title page photo: Mt. Crosin wind farm. Photo by the author.

Abstract

The assessment, mapping, and evaluation of ecosystem services is an integral part of the systems oriented management of ecosystems. Developing methods to understand the relationship between our interference in the landscape and the delivery of these services will help society to better manage our impacts on the ecosystems that sustain us. To this end, spatial planning aims to balance activities that compete for space in the landscape. Incorporating the ecosystem service approach into planning and management requires an understanding of the effects that land use decisions will have on the environment.

In Switzerland, different types of land use, including electricity production, compete directly for little available space. By 2030, this small country hopes to produce around 5,4 TWh of its electricity using renewable sources, including wind. By the time nuclear reactors are phased out in 2050, the country will require 25 TWh (93% of demand) of renewable electricity. In order to ensure long term efficient, socially acceptable and sustainable electricity production in Switzerland, land-use conflicts should be addressed and properly managed through a comprehensive and balanced process.

This paper describes an optimisation model that was developed to better understand the relationship between wind electricity production and the delivery of ecosystem services in Switzerland. It was demonstrated that using the software Marxan, originally created to resolve conservation planning problems, can help to create spatially-explicit solutions for such complicated ecosystem service trade off issues. By expressing different ecosystem services in comparable units and evaluating the costs to the system when these are lost versus the benefits gained from wind electricity production, an output of possible solutions was generated. When compared to a similar study, the current results using Marxan suggest a solution requiring 25% less turbines in the whole of Switzerland to achieve the same electricity output. This shows that using optimisation software can lead to more efficient land use predictions.

The graphical outputs generated by an optimisation can also be interpreted in different ways to assess the potential impacts on different ecosystem services as well as to other possible real solutions to resolve conflict on various scales. Parameters can be modified to suit different scenarios and data scales and so allow for flexibility in the model. The quantification of trade offs between ecosystem services and abiotic outputs is a powerful tool to share scientific findings with decision makers so that better informed policy decisions can be made.

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Contents

List of Figures	7
List of Tables	7
1 Introduction	9
1.1 Research Aims	9
2 Background	10
2.1 Switzerland's Changing Electricity Mix	10
2.2 The Ecosystem Service Approach	10
2.2.1 Defining services	10
2.2.2 Evaluating ecosystem services	12
2.2.3 Applying ecosystem services	13
2.2.4 Using the ES approach to evaluate trade offs	14
2.3 The Challenge of Policy Making Amid Ecosystem Scale Assessments	14
2.3.1 Limitations of the ES approach	15
2.4 Applying the ES Approach to the Renewable Energy Revolution . . .	16
2.4.1 Qualitative assessment of wind electricity conflicts	16
2.4.2 Quantitative assessment of wind electricity conflicts	17
2.5 Optimisation	18
3 Methods	19
3.1 Study Area	19
3.2 Modifying Marxan for the Present Study	19
3.2.1 Input files	20

3.2.2	Output files	21
3.2.3	Planning units	21
3.2.4	Target	23
3.2.4.1	Wind speed	23
3.2.4.2	Potential for wind turbines	23
3.2.4.3	Turbine selection	23
3.2.4.4	Calculating electricity output	24
3.2.5	Overall target	25
3.2.6	Cost	25
3.2.6.1	Ecosystem Service Units	25
3.2.6.2	Cultural Section	26
	Aesthetics	26
	Tourism	27
3.2.6.3	Provisioning Section	27
	Agriculture	27
	Forestry	28
3.2.6.4	Regulating and maintenance Section	28
	Biodiversity	28
3.2.7	Edge hexagons	29
3.2.8	Boundary Length Modifier	30
3.2.9	Input files used in the present study	30
3.2.10	Scenarios	33
3.2.10.1	Restrictive scenarios	34
	Avoiding areas without human infrastructure	34
	Elevation adjustment	34
3.2.11	Marxan outputs	35
3.2.12	ESU loss	35
3.2.13	Assumptions of the model	37
4	Results	39
4.1	Wind Turbine Locations	39
4.2	Electricity Output	39
4.3	ESU	40
4.4	Scenarios	41
	Unweighted ESU	41
	Provisioning services multiplied by two	45
	Provisioning services multiplied by four	46
	Cultural services multiplied by two	46
	Cultural services multiplied by four	46
	Regulating services multiplied by two	48
	Regulating services multiplied by four	48
	Areas without human infrastructure	48
	Below 1500 m	50
4.5	ESU Loss	51
5	Discussion	55
5.1	ES valuation in a wind electricity optimisation analysis	55
5.2	Evaluating trade offs between wind electricity production and ES – what are the costs?	56

5.3	Advantages of using an optimisation approach to balance the loss of ES and benefits of wind electricity production in Switzerland . . .	57
5.4	What Marxan tells us about ES in Switzerland	58
5.5	Wind electricity as part of the renewable energy mix in Switzerland .	59
5.6	Further advantages of Marxan and the ES approach	59
5.7	Limitations of Marxan and the present model	61
5.8	Future possibilities	61
6	Conclusion	63
7	Acknowledgements	65
	References	66
	Appendices	71
	Appendix A Source ES maps	71
	Appendix B Marxan results from scenario B	72
	Appendix C Marxan results from scenario C	73
	Appendix D Marxan results from scenario D	74
	Appendix E Marxan results from scenario E	75
	Appendix F Marxan results from scenario F	76
	Appendix G Marxan results from scenario G	77
	Appendix H Marxan results from scenario H	78
	Appendix I Marxan results from scenario I	79

List of Figures

1	Map of Switzerland	19
2	Work flow diagram	22
3	Average annual wind speed at 120 m	24
4	Potential wind turbine sites by Hergert (2013)	25
5	Trendscenario land use map	28
6	ES values based on conversion from source data	29
7	Boundary Length Modifier calculation	30
8	Example input <i>input.dat</i>	31
9	Example input <i>spec.dat</i>	31
10	Example input <i>pu.dat</i>	32
11	Example input <i>puvfeat.dat</i>	32
12	Example input <i>boundary.dat</i>	33
13	Example output <i>12TWh_best.txt</i>	36
14	Example output <i>12TWh_ssoln.txt</i>	36
15	Example output <i>12TWh_sum.csv</i>	36
16	Available wind turbine sites	39
17	Electricity Output of Planning Units	40
18	Unweighted combined ESU distribution	41
19	Distribution of combined unweighted ESU over potential wind turbine sites.	42
20	Selection frequency of sites in scenario A, 5TWh target	42
21	Best solutions for unweighted scenario	43
22	Selection frequency of sites in scenario A	44
23	Marxan output; scenario B, 12 TWh target	45
24	Marxan output; scenario C, 12 TWh target	46
25	Marxan output; scenario D, 12 TWh target	47
26	Marxan output; scenario E, 12 TWh target	47
27	Marxan output; scenario F, 12 TWh target	48
28	Marxan output; scenario G, 12 TWh target	49
29	Existing infrastructure in Switzerland	49
30	Marxan output; Scenario H	50
31	Marxan output; Scenario I	51
32	ESU loss	52

List of Tables

1	CICES ES typology	11
2	Selected wind turbine power generation	24
3	Conversion of ES value for Marxan	27

1 Introduction

1.1 Research Aims

Since the publication of the Millennium Ecosystem Assessment (MA, 2003), the scientific community has focused on developing a clearer understanding of the relationship between ecosystem services (ES) and how their ongoing use influences human well-being. The assessment, mapping, and valuation of these ES has become the focus of much activity in different disciplines (Kumar *et al.*, 2013; Busch *et al.*, 2012). Additionally, governments are recognising the importance of integrating ES into spatial planning as well as national environmental and economic accounting (Böhnke-Henrichs *et al.*, 2013). Combining modeling tools with spatial mapping can assist in the identification of areas important for ES provisioning, thereby predicting and resolving conflicts. This can be successfully achieved while supporting the implementation of Ecosystem-Based Management (EBM) (Gimpel *et al.*, 2013). This study aims to incorporate the ES concept into landscape planning so as to help bridge the gap between natural and social science. By way of an example application of optimisation software, real data are used to demonstrate how the ES approach can be effectively used to assess trade offs within a system and to make recommendations to policy makers.

Switzerland aims to replace a large portion of its electricity supply with renewable sources (such as wind) in order to make up for the shortfall from the planned phaseout of its nuclear reactors (Huber *et al.*, 2015). With an ambitious aim of producing 74% of its electricity via renewable technologies by 2030 (50% of which will be from hydro power), and a goal of 93% renewable-sourced electricity (around 25 TWh) by 2050, Switzerland is faced with a great planning challenge. The small country must make trade off decisions on where to place wind farms and other renewable electricity installations in order to maximise benefits (electricity production) while minimising costs (loss of services provided by the landscape). The objective of this study is to provide decision makers with a tool to manage this trade off and to help understand the optimal spatial distribution and extent of wind electricity production in Switzerland required to meet the nation's energy goals. Building on recent analyses of conflict between ES and electricity production by wind, optimisation software is used to find the best spatial solution for the country. This spatially-explicit analysis will test different ES valuations and restrictions on turbine placement in order to explore how this affects the delivery of ES now and in the future.

The particular research question to be addressed in this study is: **At what cost to ecosystem services can wind electricity be provided by the Swiss landscape?**

The subquestions to be investigated towards understanding this main topic are:

1. Can optimisation software be applied to offer spatially-explicit solutions to ecosystem service trade off analyses in order to balance costs and benefits?
2. How can ES be weighed and compared to understand the relation between existing supply and future provisioning of services when land use is changed to accommodate wind electricity production?
3. What is the optimal spatial distribution of wind electricity production in Switzerland in order to reach the country's energy goals?

2 Background

2.1 Switzerland's Changing Electricity Mix

With the planned phaseout of nuclear energy production in Switzerland, recent legislation and research has encouraged the development of alternative sources for the country's electricity supply (Huber *et al.*, 2015). Specifically, the Swiss Federal Office of Energy aims to increase the use of renewable energy and has set a goal for 10% of the country's present day electricity consumption to be produced in this way by 2030 (equivalent to about 5,4 TWh) (Segura Morán *et al.*, 2014; Huber *et al.*, 2015). Further, the goal for 2050 is to cover 93% of the demand by renewable electricity (around 25 TWh). Although the principle source of renewable electricity in Switzerland today is hydro power¹, the inclusion of wind and solar electricity production will be necessary to reach the future goal.

The demand for renewable electricity supply is growing, but so are the pressures on the landscape. In Switzerland, where land use planning has been an integral part of the national development strategy, the interaction between provisioning services and renewable electricity production has recently been assessed (Huber *et al.*, 2015). By examining the potential spatial conflict between these land uses, Segura Morán *et al.* (2014) showed that this type of development can lead to certain risks and further conflicts. Through an investigation of the combined effects of different sources of renewable electricity, the study helped to identify the relationships between these and ES and then to map the conflicts spatially. However, there was a lack of an evaluative process to communicate the extent of these relationships with stakeholders. Due to this, the study fails to fully bridge the gap between science and policy. Successfully achieving this is considered part of an important process towards ensuring efficient, socially acceptable and sustainable energy production.

2.2 The Ecosystem Service Approach

2.2.1 Defining services

When first introduced as a concept, ES were defined as the products or services from an ecosystem that are used for or contribute to human well-being (MA, 2003; Howard *et al.*, 2013). Traditionally divided into four categories of provisioning, regulating, cultural, and supporting services, these are meant to demonstrate our deep dependency on the ecosystems that sustain us. They can be expressed as units that describe the relationship between humans and ecosystems (Busch *et al.*, 2012). Building on this initial classification of ES and subject to years of expert recommendations and related study, Haines-Young & Potschin (2013) describe recent efforts by the European Environment Agency to establish a more hierarchical system of ES classification. In order to standardise the definition and classification of ES, the Common International Classification of Ecosystem Services (CICES) was developed (see table 1). The CICES system makes a clear distinction between final ecosystem services, ecosystem goods or products and ecosystem benefit. Additionally, the classification is restricted to the

¹Currently, 57% of Switzerland's electricity is produced by hydro, whereas nuclear power contributes about 37% (World Nuclear Association, 2015)

outputs of ecosystems dependent on living processes. Therefore, abiotic outputs such as wind energy are not considered ES, but classified separately. This new research has suggested that the services be divided somewhat differently than as in the past into the following general categories: *provisioning, regulating and maintenance, and cultural* (Haines-Young & Potschin, 2013). The hierarchical structure of this updated system allows for easier analysis at different spatial and thematic scales. For the purposes of this study, I will be using these more recent definitions, along with the hierarchical categories to which they belong.

Section	Division	Group	Class
Provisioning	Nutrition	Biomass	Cultivated crops Reared animals and outputs
	Materials	Biomass	Fibres from plants
	Energy	Biomass-based energy sources	Plant-based resources
Regulation and Maintenance	Mediation of waste	Mediation by biota	Bioremediation by microorganisms
	Mediation of flows	Liquid flows	Flood protection
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Pollination and seed dispersal
Cultural	Physical and intellectual interactions	Intellectual and representative interactions	Aesthetic
		Physical and Experiential interactions	Physical use of landscapes
	Spiritual, symbolic, and other interactions	Spiritual and/or emblematic	Sacred and/or religious

Table 1: Typology of ES based on CICES (based on Haines-Young & Potschin (2013)). Green cells indicate the services chosen as part of the analysis in this study.

The CICES system divides ES into 'Section', 'Division', 'Group', and 'Class'. Twenty Groups and forty eight Classes are proposed. A subsequent 'Class Type' category is added where ES are placed based on the ecosystem being considered (terrestrial, freshwater, or marine, for example). This allows for some flexibility in where specific examples of named ES are ultimately classified. CICES gives examples of which ES can be placed into different Class Types, but the list is certainly not exhaustive. This means that the user is responsible for providing adequate information to help with the classification of the service studied. In the present study, to keep the terminology consistent with the data sets used, I have used a mix of Division, Group, and Class titles (see Methods). The five ES studied cover three Sections; one ES is defined at the broad Division level, one at the Group level,

while the other three are defined at the Class level. Although the terminology I use for the ES examined here does not match the CISES system exactly, I will explain later how these terms relate to those definitions.

ES are linked to the spatial dimension of the area in which they occur (Busch *et al.*, 2012; van Wijnen *et al.*, 2012) and as such are good candidates for use in spatial planning. Even so, they have rarely been applied to planning studies for reasons that will be discussed below (Broekx *et al.*, 2013). Additionally, ES can often co-occur and interact on a wide range of spatial and temporal scales.

Recent debate has focused on an extended view of the ES definition. Landscape services are the “flow of ES to society provided within a landscape”, as defined by Willemsen *et al.* (2012). However, Kienast *et al.* (2009) and others define the capacities, or stocks, to provide goods and services as the landscape functions. In this latter case, the goods and services are termed the ‘flows’. Segura Morán *et al.* (2014) use the term landscape services to refer to services such as renewable energy production. All of these terminologies are an attempt to emphasise the link between the provided services and the ecosystem’s ability to deliver these. Regardless of the often confusing terminology, the essence of the argument is that not only are the services themselves of importance, but the landscape’s ability to deliver these functions must be incorporated into management plans.

In the present study, I will continue to use the term ES in order to avoid confusion. This applies to all of the services that I will incorporate into the model, regardless of the typology that they fall into. For instance, the aesthetic aspects of the landscape that are used in this analysis are a combination of peoples’ appreciation of the landscape and how this relates to their interactions with physical features of the environment. Moreover, it is the landscape’s ability to deliver aesthetic enjoyment to those who use it for cultural and other reasons. As will be seen later, I term this service simply *aesthetics*. Some authors may insist this is a landscape service as opposed to an ES. In the end, the terminology is less important than the concept of successfully integrating these services into the optimisation model.

2.2.2 Evaluating ecosystem services

A variety of tools have been developed for the mapping, valuing, and quantification of ES (Busch *et al.*, 2012; O’Higgins & Gilbert, 2014; Grêt-Regamey *et al.*, 2015). The economic valuation of ES is a method to assess and trade the effects of human activities in the provisioning of these services. As such they form a natural bridge between the natural and social sciences. However, the complicated relationship between ecosystems and the final service provided has caused some difficulty in the valuation of ES (O’Higgins & Gilbert, 2014). Still, the concept has been widely welcomed. For instance, a recent European Union directive for member states to map their ES has produced a large set of data to be used by various institutions and towards many applications. Overall, the valuation of ES is data-dependent and can be resource-intensive, but it is imperative that appropriate evaluative techniques be employed in order for any study to reflect real-world situations and offer pertinent and realistic solutions.

One of the major problems with ES valuation is that in many cases, a value for the service provided cannot be expressed in monetary terms. By failing to attribute a market value to these ES, it is difficult to incorporate them into traditional eco-

conomic models. Although a monetary value isn't a *prerequisite* for inclusion of ES in a plan, valuing them in some way allows them to illustrate important relationships such as economic externalities of environmental processes or change (O'Higgins & Gilbert, 2014). Alternately, because the ES concept is grounded in ecology, these services can be instead be defined and measured using ecologically relevant units (Böhnke-Henrichs *et al.*, 2013), so long as this is appropriate for the particular study. Another drawback is that the complex interactions between ES make it difficult to predict their behaviour in a changing landscape. It is often assumed that there is a linear relationship between ES and their provisioning, but this is not always the case (Bennett *et al.*, 2009). Additionally, there is often a mismatch in the scale on which an ES is evaluated and that in which it interacts with others, causing great difficulty in appropriate ES valuation (Broekx *et al.*, 2013; Lester *et al.*, 2013). Most ES are not good surrogates for each other and must be assessed separately before they can be combined for study (Bennett *et al.*, 2009).

While the assessment of ES can be a challenging topic with many stakeholders who have differing opinions, Switzerland benefits from a supportive system that helps to standardise the process; an indicator-based monitoring system (LABES) has been developed to map the different landscape features in detail (Kienast *et al.*, 2015). This data, along with additional mapping projects undertaken by Hergert (2013); Hergert *et al.* (2014); Segura Morán *et al.* (2014), result in a large amount of information available to address the challenge of spatial planning in this small country. This sets the stage for the development of a tool to effectively communicate ES trade offs within the growing renewable energy sector in Switzerland and towards fulfilling its ambitious future electricity needs.

2.2.3 Applying ecosystem services

The ES approach, as described by Busch *et al.* (2012), uses their spatial dimension expressed in certain units to address, describe, and predict the relationship between ecosystems and human activities, even when markets cannot do so (Böhnke-Henrichs *et al.*, 2013). It focuses on the interconnectivity of the natural environment, leading to a more complete, holistic and integrated construction of the socio-ecological system (Baker *et al.*, 2013). This approach helps to identify and quantify the links between human welfare and the environment and thus to evaluate the effects of management interventions (Böhnke-Henrichs *et al.*, 2013). This model results in the effective framing of the environment in terms of communication with stakeholders and decision makers (Baker *et al.*, 2013). By dealing with 'bundles' of services, the ES approach allows decision makers to reflect on the impacts of their plan on the environment rather than only vice versa by attributing value to services provided. This is a true application of EBM (Grilli *et al.*, 2013).

Attributing value to services which were previously not incorporated into models has brought different ideas to the forefront of spatial planning. For instance, the importance of non-extractive ES can be stressed by including cultural services in an assessment (Ruiz-Frau *et al.*, 2013; Hergert *et al.*, 2014). In instances where public opinion affects regulation, the perceived values of environmental aspects such as aesthetics can be assessed and included in policy creation (Meyerhoff *et al.*, 2010). Considering ES when making decisions about the use of ecosystems can

provide anthropocentric arguments for policies that previously would have not been seen as advantageous (Schröter *et al.*, 2014).

2.2.4 Using the ES approach to evaluate trade offs

One area of environmental assessment where the ES approach has proven to be very useful is in addressing costs and benefits and in trade off analyses (Anderson *et al.*, 2009; Carpenter *et al.*, 2009; Kumar *et al.*, 2013; Lester *et al.*, 2013; Segura Morán *et al.*, 2014; Schröter *et al.*, 2014). Well-informed decision making regarding trade offs requires that all costs and benefits be taken into account and with this method, regardless of the evaluative criteria, attributing value to ES encourages this to take place (De Groot *et al.*, 2010). Cost-effective conservation that minimises opportunity costs in terms of foregone commodity production is an example of this concept in action (Schröter *et al.*, 2014). From a broader perspective, any policy changes in land management will lead to a trade off in service supply by the landscape affected (Willemen *et al.*, 2012). To effectively minimise this trade off in supply of different services, land management actions should be governed and guided. The ES approach is a method to attain just that.

It is important to recall that trade offs, as perceived by the ES approach, are interactions from a societal point of view. By assessing the system as a whole, this concept allows for an objective evaluation and leads to an objective outcome. When the cost versus benefit relationship within a system is analysed from a subjective viewpoint that doesn't necessarily incorporate the whole system, then the situation results in a conflict. In these scenarios, there is a perceived winner and a loser. The ES approach allows for the weighting of different ES so that decision makers can focus their management priorities in these cases (O'Higgins & Gilbert, 2014). By recognising that modifying services may compromise the delivery of others, conflict between policies and conservation or management goals can be avoided or solved (Howard *et al.*, 2013). Within the context of the present study, Huber *et al.* (2015) explain that, in order to ensure that renewable energy is socially accepted, current and future land-use conflicts should be assessed.

The present study offers a methodology to use the ES approach in assessing trade offs with wind electricity production in Switzerland. Using the ES approach in evaluating the trade offs with renewable sources of energy has three great advantages according to Hastik *et al.* (2015). First, multiple environmental issues can be assessed together. Second, it allows a systematic comparison of energy system changes and their effects on different ES. Third, it serves to bridge the gap between the social and natural sciences by facilitating the decision making process and encouraging dialogue among stakeholders.

2.3 The Challenge of Policy Making Amid Ecosystem Scale Assessments

According to Broekx *et al.* (2013), the key challenge of policy-making today is how to minimise the degradation of ES with ever-increasing demands for their services. The idea of EBM of natural systems implies an attempt to link actions and concepts on a large scale (Böhnke-Henrichs *et al.*, 2013; Gimpel *et al.*, 2013). By integrating ecological, social, and economic interests, decisions can be made

with a balanced view of the management outcome. These concepts have been effectively applied in marine and terrestrial systems, but rely heavily on information about ES.

The concept of ES is located at the science–policy interface where they translate the link between ecological processes and human well being in a way that, critically, can be understood by decision-makers (Böhnke–Henrichs *et al.* , 2013; Helming *et al.* , 2013). By effectively communicating scientific knowledge at the implicit level of policy, the complex interactions between ES can be presented in such a way that informed decisions can be made.

To effectively manage ES on an ecosystem scale, decision-makers need to know how ecosystems function, how humans benefit from these ecosystems, how human activities impact these ES, and how human activities can be most effectively influenced through policy interventions (Kumar *et al.* , 2013). Much of this information is collected and prepared by scientists who then have to communicate the results to those who make policy. The difficulty encountered in many present-day decision-making systems revolves around their inability to incorporate natural capital into decisions. This requires policy-makers and scientists to foster innovative solutions that aim to reduce the knowledge gap between the social and natural sciences (De Groot *et al.* , 2010; Howard *et al.* , 2013). To tackle this problem, a great deal of research has focused on the integration of ES in landscape planning, land management, and decision making (De Groot *et al.* , 2010; Helming *et al.* , 2013; Levin *et al.* , 2013). These decisions relate to spatially oriented questions of how and where the landscape can be modified in order to enhance the provision of one or more landscape services. Although the importance of combining these concepts is clear, the poor understanding of how ES are connected and issues relating to their valuation has limited the effectiveness of these methods.

In line with the concept of EBM, the landscape service approach to land management incorporates a comprehensive landscape assessment (Segura Morán *et al.* , 2014). Once established, this information can be combined with the ES approach to understand the outcomes of planning decisions. This process is also based, however, on detailed knowledge of the relationships within the ecosystem. Therefore, in order for this approach to bridge the gap between science and policy, we first must comprehend this often complex topic.

2.3.1 Limitations of the ES approach

There are several drawbacks of using the ES approach in spatial planning and management. For example, the legal framework within which most policy decisions are made may not be open to the system of ES valuation that is still in its infancy. Uncertainty in the valuation of and relationships between ES can impede their use at the decision making level. Also, ES may not be relevant at the same spatial or temporal scales on which decision making takes place (Baker *et al.* , 2013), leading to a discrepancy between the decisions and affected parties. In the end, the ES approach is only a guideline and the actual management decisions may be made with other, non-integrated aspects of the system in mind.

2.4 Applying the ES Approach to the Renewable Energy Revolution

Among other applications, the ES approach allows for the assessment of a range of environmental issues associated with expanding renewable energy exploitation (Hastik *et al.*, 2015). The production of electricity through these new technologies is not considered an ES onto itself, but instead represents an abiotic output (Haines-Young & Potschin, 2013) which must be considered separately. In general, due to this and other factors, energy planning has difficulty integrating ES (Helming *et al.*, 2013). Assessing and evaluating this conflict is a powerful tool to help bridge the gap between science and policy in a field that is becoming increasingly important as governments turn to developing renewable sources of energy production.

Few studies have concentrated on the spatial assessment of the conflict between renewable energy and ES (Segura Morán *et al.*, 2014; Huber *et al.*, 2015). Among these are several analyses of wind electricity development. The siting of wind farms often results in negative effects on some aspects of the environment (Leung & Yang, 2012). To integrate social and ecological constraints of wind farm construction and to mitigate the negative effects, the ES approach can be used (Grilli *et al.*, 2013). The end result is the balance between the costs borne by the entire system and resources gained by the installation and operation of a wind farm. From the view of spatial planning, wind turbines are in direct competition for space with other land uses and related ES (Meyerhoff *et al.*, 2010). There are a variety of approaches, both quantitative and qualitative, that have been used to illustrate this conflict, with varied levels of success.

2.4.1 Qualitative assessment of wind electricity conflicts

The trade offs between ES and abiotic outputs can be evaluated and interpreted in different ways; graphically or qualitatively. Conflict mapping has been used several times to understand the conflict between wind electricity production and ES competing for space (Ruskule & Veidemane, 2011; Hergert, 2013; Lester *et al.*, 2013; Hergert *et al.*, 2014; Huber *et al.*, 2015). This spatially-explicit modeling aims to intersect visual representations of ES (including electricity production) in order to evaluate conflicts.

Segura Morán *et al.* (2014), for example, demonstrate that evaluated ES can be mapped alongside the landscape's electricity production potential in order to highlight areas of high or low conflict. By intersecting map layers directly using geographic information system (GIS) software, the conflicts between services were assessed. Huber *et al.* (2015) take this one step further and develop models for electricity production in a conflict-free area. Areas across the whole of Switzerland were assessed as being suitable for wind turbines in this study. The problem however, from a management perspective, is that the described relationships are not directly quantified and arbitrary levels of conflict are used. This may not offer the most comprehensive method to communicate these findings with decision makers.

Von Der Dunk *et al.* (2011) use an even more passive method to evaluate conflicts. By researching print media, the authors correlate published information with conflict analysis. This may be somewhat effective in a country like Switzerland, where there is high landscape awareness (Huber *et al.*, 2015), but the results

will be extremely difficult to extrapolate. The studied scale may also vary widely between areas. Also, there is certainly a bias in the information gathered which may not reflect stakeholders' views if incorporated into a management plan. It is important to incorporate the interests of all relevant parties in spatial planning (Ruiz-Frau *et al.*, 2013).

Ruskule & Veidemane (2011) interviewed stakeholders to determine what was important to them in their analysis of a marine spatial plan (MSP) in the Baltic Sea. This resulted in good coverage of interest groups' concerns, but the further mapping of conflict was conducted without a sound methodology that incorporated the ES approach. Again, the effectiveness of the analysis suffers from generalised conflict mapping.

2.4.2 Quantitative assessment of wind electricity conflicts

A different approach to conflict assessment and analysis attempts to quantify the relationship between wind electricity production and ES provisioning.

Some studies have used the ES approach to tackle complex spatial planning issues on land and in the sea. Gimpel *et al.* (2013) employ a spatial risk assessment tool to highlight the conflicts between offshore wind turbines and important fish habitat in the North Sea. The environmental impacts of other sea uses on the fishery were assessed with this tool. It was determined that offshore wind farms will increase the conflict potential, but it remains to be seen how to quantify this relationship. This complicated method focuses on the effects of just one ES, however, which has limited use for decision makers.

Grilli *et al.* (2013) develop a 'Wind Farm Siting Index' to assess the suitability of a location to an offshore wind farm. This complex assessment tool is based on a variety of variables, thereby increasing the potential for errors and limiting its scope. This index then has to be assessed vis à vis the other ES. This technical interpretation may not be suitable for communication with decision makers.

Multicriteria decision evaluation frameworks have been used by some researchers to evaluate conflict in similar studies (Gamboa & Munda, 2007; Kannen, 2014). This analysis-heavy attempt to include social elements in the process introduces bias at several stages and the use of compatibility matrices requires site-specific information that may not always be available. This method, too, is heavily dependent on concepts that may be difficult to effectively communicate to policy makers.

Göke & Lamp (2012) demonstrate how an effective ES approach can be used to quantify and evaluate the conflicts posed by offshore wind farms on the MSP in the Baltic Sea. The methodology introduced allows for different ES to be compared and combined in an attempt to solve spatial issues. This is further enhanced by using optimisation software that evaluates conflicts in such a way that the relevant ES can be weighted. The present study incorporates some of the ideas and methods from this marine study and transposes it into a terrestrial setting where the trade off with ES is assessed differently.

2.5 Optimisation

To tackle the complex problems posed by wind electricity development in a spatially-explicit management landscape, the ES approach can be combined with other tools. The costs and benefits of competing ES can be weighed and modeled in order to better understand their relationships. When this information is presented to decision makers, they are better able to make informed policy decisions based on their requirements and the available data. Meyer *et al.* (2009) argue that it is important for a spatial analysis model to be able to specify a decision maker's preferences. To this end, a combination of model tools and optimisation may reduce the complexity of the problem and make the results more easily grasped.

Various optimisation models have been developed and applied in the field of spatial planning and land management (Orsi *et al.*, 2011). However, some problems have emerged with the traditional models. For instance, problems of scale become apparent when the models fail to account for local peoples' needs. Further, an *optimal* and *repeatable* solution is important for communication with decision makers.

Marxan is optimisation software that was designed as a tool to provide decision support for systematic nature conservation planning (Ball *et al.*, 2009; Göke & Lamp, 2012). To minimise cost while maximising benefits (eg. protected species), the program evaluates different potential spatial management decisions. By combining a variety of inputs, it allows for direct economic costs to be evaluated against other estimates. In the context of conflicts in the field of spatial planning, this program has shown to be flexible and effective in its proposed solutions (Chan *et al.*, 2006; Kiesecker *et al.*, 2009; Bolliger *et al.*, 2011). In the planning of marine protected areas, for instance, it successfully quantified the benefits of integrating extractive and non-extractive interests (Ruiz-Frau *et al.*, 2013). The heuristic algorithms that the program uses are good for planning as they can incorporate large data sets and provide a set of near-optimal solutions in the analysis (Nackoney & Williams, 2013).

Marxan has already been used successfully as a conservation and land planning tool in Switzerland (Bolliger *et al.*, 2011; Götz, 2014). Additionally, it has been applied to MSP with offshore wind farms in other areas (see previous section). This latter study was the first time Marxan was used to address issues of wind electricity production from an optimisation perspective while using the ES approach. By combining different costs into the model (both economic ones relating to the monetary cost of turbine installation as well as impact on other ES), the authors demonstrated how balancing conflicting needs results in a spatial solution unique to the restrictions imposed on the system. The present study, however, is the first to use Marxan as a spatial planning tool for land-based electricity production.

3 Methods

3.1 Study Area

Switzerland is a country in central Europe that can be divided into five major geographical zones (Bolliger *et al.*, 2011) (figure 1). The Central Plateau is nestled between the Jura Mountains to the northwest and the Alps to the southeast. This larger mountain range can be further divided into three regions; the Northern, Central, and Southern Alps. Switzerland's 41,285 km² are bordered by France, Germany, Austria, Lichtenstein, and Italy (Wikipedia, 2015). Around 70% of the landlocked country is steep or mountainous terrain, with the remaining 30% located on the Central Plateau, where most of the larger cities are located alongside rivers and lakes, forests, and agricultural zones. The country's 8 million inhabitants live mostly in the Plateau area and the overall density is about 200/km². In all, 48 of Switzerland's mountains are over 4,000 metres and a large proportion of the country is in these higher elevations.

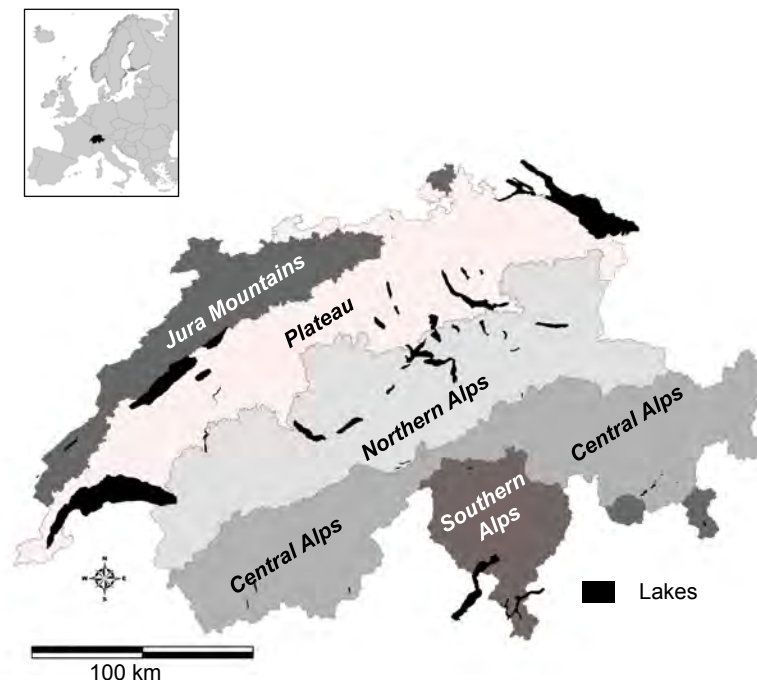


Figure 1: Location map of Switzerland in Europe showing the major geographical regions (after Bolliger *et al.* (2011)).

3.2 Modifying Marxan for the Present Study

The program MARXAN (Game & Grantham, 2008; Ball *et al.*, 2009; Bolliger *et al.*, 2011) was used to optimise the selection of wind turbine sites across Switzerland. Since Marxan was originally designed as a conservation planning tool, some of the inputs, outputs, and parameters were necessarily adjusted for use in the present study. Once they were prepared, these were introduced into the program so that it correctly conducted the optimisation algorithm. The following outlines the file types necessary in order for Marxan to run properly.

For an overview of the work flow followed in the present study, please refer to figure 2.

3.2.1 Input files

There are several input files required for Marxan to run an optimisation. Each is in a *.dat* file format. Four files are necessary, while another is used to establish relationships between Planning Units (PU) (Game & Grantham, 2008).

input.dat

This input parameter file contains information that is needed to instruct the program how to conduct and assess the optimisation. Included here are the number of iterations, the number of runs, the path filenames, the specific type of annealing to be used, and so forth. All of these settings can be adjusted by the user.

pu.dat

The planning unit file is a list of the individual PU, each with a unique identification number, along with a cost value contained within each. Only one cost can be given for each PU. Generally, this is a value that differs between PU.

spec.dat

Contained in the conservation feature file is information about the features being considered, such as their name, targets, and representation requirements.

puvfeat.dat

The planning unit versus conservation file contains information on the distribution of conservation features in each of the PU. Multiple features can be listed, each with a value for the given PU. The sum of these conservation features represents the target to be achieved.

boundary.dat

This is a measure of the boundary length, or 'effective length' of shared boundaries between PU. Using a plugin for ArcGIS (ESRI, 2015), a file containing the actual length between each of these units can be calculated. Any PU that borders another will be assigned a value for the length of this association. Although not required, this file allows the user to specify a degree of connectedness between PU through use of the Boundary Length Modifier (BLM).

3.2.2 Output files

Marxan produces a variety of outputs that must be interpreted in order to better understand their significance. These are produced as *.txt* files and are converted into *.csv* format by the user in order to be exported for use in other programs.

scenario_sum.txt

For each run of a particular Marxan setup, a separate file is generated showing whether each PU is selected or not. The *scenario_sum.txt* file compiles the results from each run; the *Score* that helps select the best run, the *Cost* associated with each, how many *Planning_Units* were involved in the solution, the length of the boundary of the reserve system (labeled *Connectivity*), and if there was a *Shortfall* in reaching the target.

scenario_best.txt

The program then selects the run with the lowest value (based largely on the associated cost for each run) and labels this as the *best solution* for the optimisation. This may not represent the ideal system of selected PU, but it shows the one with the lowest associated cost and objective function value (This objective function is explained in detail by Ball & Possingham (2000)). The file has two columns; *planning_unit* (PU id) and *solution* (1 = included in solution, 0 = not included).

scenario_ssoln.txt

The summed solution file provides the selection frequency of each planning unit across all runs. Each line has the PU id and how many times it was selected as a solution in individual runs. There are two columns in this file; *planning_unit* (PU id) and *number*, which represents the number of times that each PU was selected within the 100 runs.

3.2.3 Planning units

Although it can be run with any shape of PU, Marxan has been shown to work especially well with hexagons. One great advantage is that the actual boundary length between adjacent PU can be easily calculated, offering an important tuning parameter for the software (Göke & Lamp, 2012). In the present study, hexagons were used to represent the sites that could be used for wind turbine locations. Based on recommendations from Lütkehus (2013), Segura Morán *et al.* (2014), and Huber *et al.* (2015) regarding the minimal distance between wind turbine sites, hexagons with an incircle radius of 400 metres were used. These shapes have an edge length of 461 m, a diagonal of 800 m, and an area of 554,256 m². The literature suggests a minimum distance of 456 m between turbines to account for variable local conditions and turbine types, etc. The distance was almost doubled in this analysis, however, for a few reasons.

First, the hexagons are built around as little as one Ha of suitable wind sites (based on previous analysis), meaning that it is possible that there is only a small part

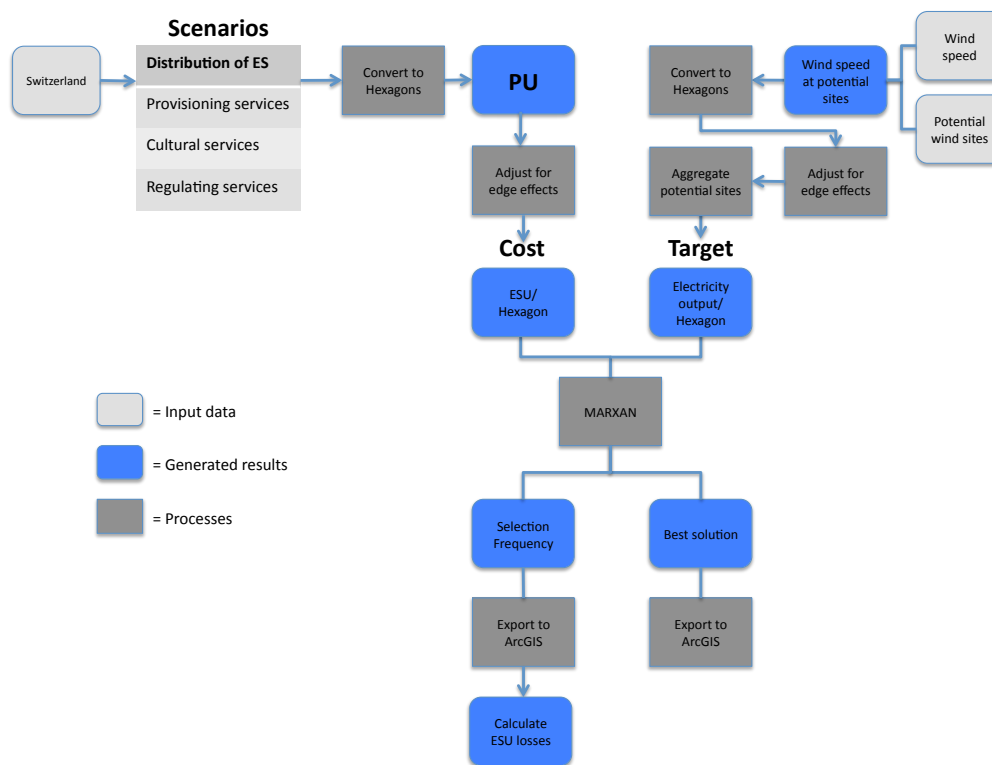


Figure 2: Work flow diagram for preparing data, running MarXan optimisation, and presenting results. All steps aside from those in MarXan were conducted using ArcGIS.

of the area that can actually be used for wind power generation. To maximise the probability that a chosen hexagon is actually usable, they were kept large. Second, assuming that a wind turbine can be built anywhere on a hexagon suggests that two turbines *could* be built close to one another if they are built in adjoining hexagons. Maintaining a large PU area allows for room to move these conflicting turbines in a real situation. Third, in practice, it seems that the minimum required distance between wind turbines varies according to local conditions. Often, turbines are built much closer together, as is the case in many extant wind farms. In the present model, I maintain that, in reality, multiple wind turbines could be built on a hexagonal PU, provided there is enough suitable area within that space. By keeping the PU large, I am allowing for flexibility in the planning of future wind farms.

By incorporating a larger area for PU in the present study, flexibility of turbine siting is respected while maintaining the requirements suggested in the literature and other models.

In a later step, suitable wind turbine locations comprised of two or less adjoining hexagons were removed from the list of available sites. This is an extension of the reasoning above so that, in the case that only one turbine can effectively be built on each hexagonal PU, the minimum requirements of a wind park are met. Economic and practical reasons often dictate that more than a few turbines must

be planned at a farm before it is built.

The entire area of Switzerland was divided into 183,860 hexagons using ArcGIS. Each hexagon was assigned a unique identification number that was used throughout the model. This is a similar method to other studies using this software (Göke & Lamp, 2012; Makino *et al.*, 2013).

3.2.4 Target

Marxan optimises the sites selected in order to reach a set objective. This target represents an accumulation of a given feature that is used to balance the costs associated with the sites being included in a solution. Using a selected PU as a wind turbine site will result in a given electricity output which, when calculated across the entire system, represents the theoretical amount of electricity generated by a collection of wind parks.

The location of a wind turbine is critical to its potential power output (Bohrer *et al.*, 2013). With this in mind, to calculate the electricity output of each PU, three factors were taken into account:

1. Available wind speed
2. Suitability of the site for wind turbines
3. Power output generated by a selected wind turbine model

3.2.4.1 Wind speed

The minimum required average wind speed used in preparing renewable energy strategies in Switzerland is 4.5 m/s (Office Fédéral de l'Énergie, 2004; Meteo Test, 2012). Measurement of wind speed is used to calculate electricity output of a given model of wind turbine. Hergert (2013) and Segura Morán *et al.* (2014) used data from Meteo Test (2012) to map wind speed at a hub height of 120 m. These speeds are shown in figure 3.

3.2.4.2 Potential for wind turbines

Hergert (2013) and Segura Morán *et al.* (2014) then used a method designed in part by Meteo Test (2012) to assess the suitability of sites to wind turbines across Switzerland. The selected sites were far enough from buildings, urban areas, bodies of water and located on flat to gradually sloping terrain. Figure 4 shows the resulting map of areas suitable for wind turbines in Switzerland, along with the matching maximum nominal wind speed.

3.2.4.3 Turbine selection

Here, the Vestas V112-3.0 MW model was selected, as it performs well in low wind conditions (starts at 3.0 m/s) and is suitable for the Swiss climate (Vestas Wind Systems, 2012). These turbines have a hub height of around 120 m and rotor diameter of 112 m.

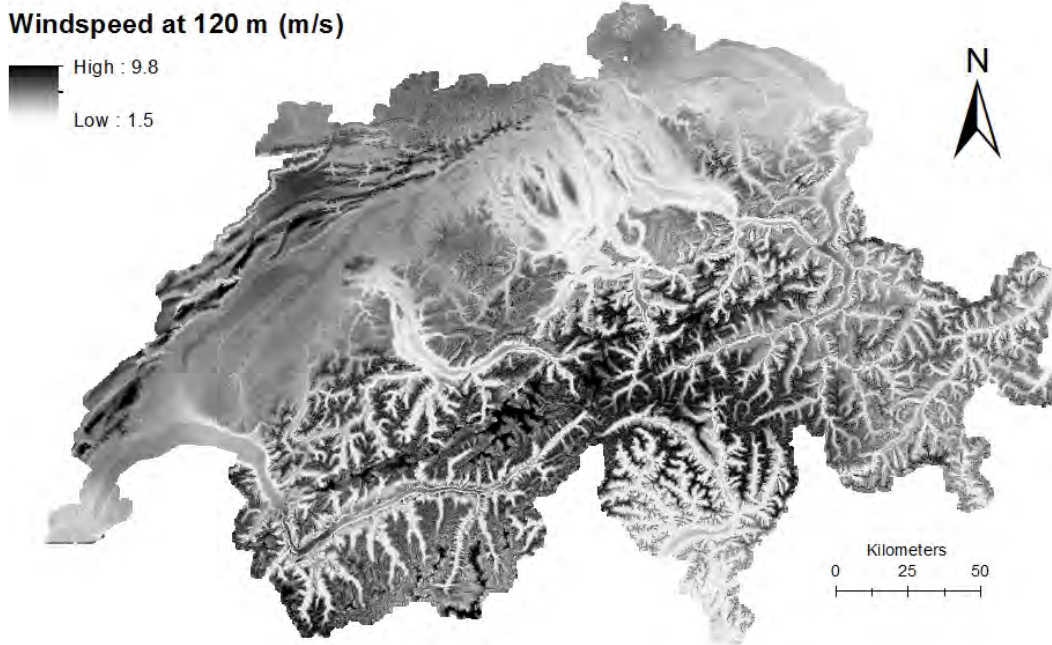


Figure 3: Average annual wind speed calculated at a height of 120 m in Switzerland.

Nominal wind speed m/s	Full load hours h/yr	Operating hours h/yr	Power production MWh/yr
4.0	1276	6874	4832
5.5	2124	7448	6376
6.5	2999	7799	7702

Table 2: Power generation of Vestas V112 3 MW turbine as calculated using (Meteotest, 2015).

3.2.4.4 Calculating electricity output

ArcGIS was used to combine the wind speed (raster) and suitable sites (feature class). The extract by mask function was employed to evaluate all suitable areas where wind speed was above 4.5 m/s. Three categories of wind speed were regarded: 4.5–5.4 m/s, 5.5–6.4 m/s, and >6.4 m/s, following Segura Morán *et al.* (2014). This layer was then intersected with the PU layer to identify all PU with adequate wind speed to justify building a wind turbine. Then, PU were aggregated to 3 or more connected hexagons as it was assumed that economic reasons would make it impractical to build less than 3 turbines at a given site. The highest nominal wind speed in a given potential turbine location was used to assign it to one of the three categories of wind speed. Based on a supplied calculator of electricity output (Meteotest, 2015), the potential electricity generated (MWh/yr) by a single turbine at each potential site was assigned to the PU. Table 2 shows the calculated electricity output of the Vestas V112–3.0 MW turbine at various wind speeds.

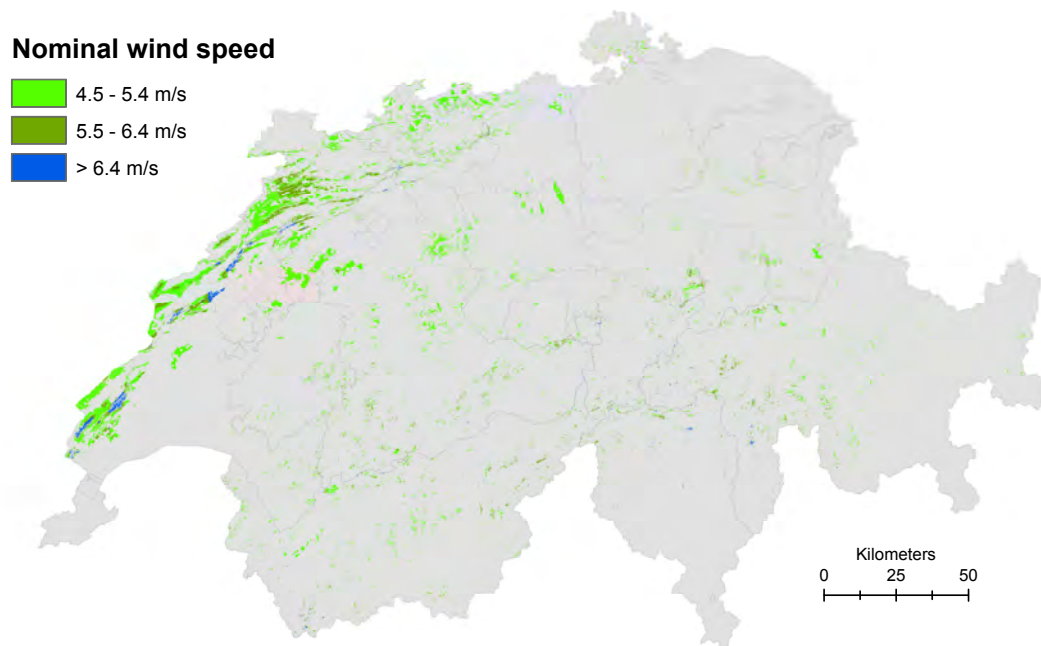


Figure 4: Areas for potential wind turbine locations in Switzerland based on analysis by Hergert (2013).

3.2.5 Overall target

As part of the Swiss energy strategy (Meteo Test, 2012), renewables are meant to make up a large part of the future energy mix. In a present-day scenario, a maximum of 14.5 TWh/yr is calculated to potentially come from wind generation (with a minimum wind speed of 4.5 m/s). Hergert (2013) calculated that, given realistic restrictions on wind turbine sites, Switzerland can expect to generate less than 4.0 TWh. Segura Morán *et al.* (2014) found that, when aiming to severely limit conflict with a set of ES across the country, 5 TWh of electricity could be generated by wind. To keep within this range and in order to investigate the effectiveness of the program, overall electricity targets of 5, 8, 10, and 12 TWh/yr were applied to the Marxan runs.

This setup allows Marxan to easily calculate the overall electricity output of a selection of sites, by summing up the individual outputs of each hexagon in a solution.

3.2.6 Cost

3.2.6.1 Ecosystem Service Units

In order to easily compare different ES, an arbitrary, non-monetary unit was used in the present study. The 'Ecosystem Service Unit' (ESU) represents an arbitrary amount of service provided. This allows different ES to be evaluated collectively by Marxan as it uses one single cost in its optimisation analysis. Each ES used in this analysis was evaluated on a 100 m X 100 m (ha) grid and each pixel was

assigned an ESU for that particular ES between 0 and 4. For the original, un-weighted analysis of ESU, each Ha pixel could have a maximum value of 20 (5 individual ES valued between 0 and 4). Summary statistics were then used in ArcGIS to calculate the value of ESU in each hexagonal PU. Finally, the ESU of the five ES calculated in each PU were added together as the total ESU for that hexagon. This number was entered into Marxan as the 'Cost' associated with each PU.

The ES used in the present analysis belong to three themes of the CICES classification system (table 1 after Haines-Young & Potschin (2013)). Two types of *provisioning* services are analysed. First, cultivated crops are considered along with reared animals and their products (*Nutrition Division, Biomass Group*) and treated as a single ES that I term "**agriculture**". Second, fibres from plants (*Materials Division, Biomass Group*) are here considered as "**forestry**". The two services examined from the *cultural* Section belong to the *Physical and intellectual interactions Division*. For the present study, I use the terms "**aesthetic**" to represent the *aesthetic* Class of ES belonging to the *Intellectual and representative interactions Group* and "**tourism**" as an example of the *physical use of landscapes* Class in the *Physical and experiential interactions Group*. The third Section, *regulation and maintenance* is represented by the *Maintenance of physical, chemical, biological conditions Division*. This final ES that I term "**biodiversity**" is an aggregate term that includes several aspects of the ecosystem important for its proper functioning. It is important to note that electricity from wind (discussed earlier) is not considered an ES by the CICES definition. Instead, it is a distinctly classified *abiotic output* of the environment.

Some of the data sets used in his study represent different time periods. The source data for agriculture and forestry (*provisioning Section*) are from predicted land use scenarios in 2050 while the cultural and biodiversity Sections are more current (from 2011). This was done to demonstrate that the model can successfully accommodate different data sources and to emphasise that these differences will be incorporated into a cost calculation regardless of origin. This underscores the need to ensure that the most appropriate data are used in an analysis; the quality of the output will rely heavily on this. In the present study, I aim to stress the range of data that can be used while demonstrating the model's flexibility.

The following assignment of ESU for the five ES is the original distribution to be used in the analysis. The preliminary conversion of source data into ESU are summarised in table 3.

3.2.6.2 Cultural Section

Intellectual and representative interactions Group

The model for the Intellectual and representative interactions Group (termed simply "aesthetics" in the present study) is based on the result of surveys conducted to identify appreciation of the landscape that were then combined with the relevant features. Figure 6a is adapted from Segura Morán *et al.* (2014) who used the LABES Indicator 24: 'Schönheit der Landschaft'. This data set was re-sampled from 50X50 m to 100X100 m in order to assess all of Switzerland at the same scale.

ES	Quantitative value	Qualitative value	Marxan value
Aesthetics	0	None	0
	0 - 0.75	Low	1
	0.75 - 1	Med	2
	1 - 1.75	Med-high	3
	1.75 - 2	High	4
Tourism	0 - 0.005	None	0
	0.005 - 12	Low	1
	12 - 20	Med	2
	20 - 33	Med-high	3
	33 - 76	High	4
Agriculture		Overgrown	0
		Closed forest	0
		Open forest	0
		Urban	0
		Arable agriculture	2
		Pasture agriculture	4
Forestry		Overgrown	0
		Closed forest	2
		Open forest	4
		Urban	0
		Arable agriculture	0
		Pasture agriculture	0
Biodiversity	0 - 0.25		1
	0.25 - 4		2
	4 - 6		3
	6 - 9		4

Table 3: Conversion of source ES values to ESU for the original Marxan analysis

Physical and experiential interactions Group

Similar to the aesthetic evaluation, the mapping of physical and experiential interactions value in Switzerland is the combined result of surveys and landscape features. In the present study, this ES is termed “tourism”. The data used here are based on the tourism potential map developed by Segura Morán *et al.* (2014). Figure 6b shows the distribution of this ES divided into five categories based on the values found in that study. This classification is based on the natural breaks function within ArcGIS.

3.2.6.3 Provisioning Section

Nutrition Division

Based on the ‘Trend’ scenario presented by Price *et al.* (2015), the extent of different agricultural land uses across Switzerland were mapped. Figure 5 shows the different categories of land use predicted in the year 2050 based on the current trend. This future scenario was used because it represents a realistic situation within the time frame required by the Swiss energy strategy. Areas in this data

set that were overgrown, forested, or in urban places were given a value of 0. Arable agriculture was given a value of 2 ESU, while pasture agriculture, used for domesticated animals, was given a value of 4 ESU. Since I have combined two different ES into one Group, I am taking advantage of the hierarchical CICES structure. The main reason that I have done so is due to the available data sets that incorporate only two types of agricultural land use; arable or pasture.

Materials Division

The same source, Price *et al.* (2015), was used to map ES derived from forests. Based on Figure 5, areas not covered in forest were assigned a value of 0, those covered by open forest a value of 2 ESU, and those with closed forest a value of 4 ESU. The services gained from a closed forest are assumed to be greater than those from a more open landscape. Figure 6d shows the conversion of this source data into ESU used in the present study.

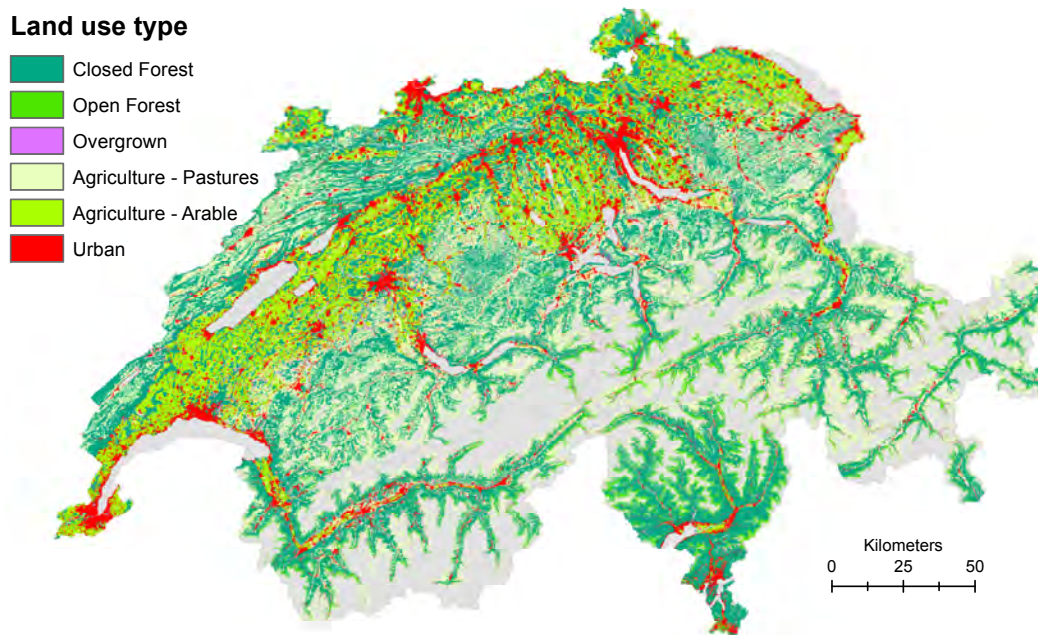


Figure 5: Trends scenario land use map adapted from Price *et al.* (2015).

3.2.6.4 Regulating and maintenance Section

Maintenance of physical, chemical, biological conditions Division

This CICES Division incorporates several different Groups and Class of regulating services. For this study, the ES is termed “biodiversity”, reflecting the understanding that an ecosystem, with many interconnections, is more resistant to pressures put on it.

The distribution of biodiversity value in Switzerland is based on analysis by Se-

gura Morán *et al.* (2014). This data incorporates important habitat areas as well as different indicators for diversity. It is an aggregation of different sources, sometimes called habitat, and sometimes biodiversity. I will continue to use the term biodiversity with the understanding that it includes habitat information and various species inventories. To convert values from the source data, the natural breaks function in ArcGIS was used. The original values between 0 and 9 were translated into ESU between 0 and 4.

All of the other spatially-explicit source data can be found in appendix A.

The resultant ESU distribution for each of these ES used in the present study is displayed in figure 6.

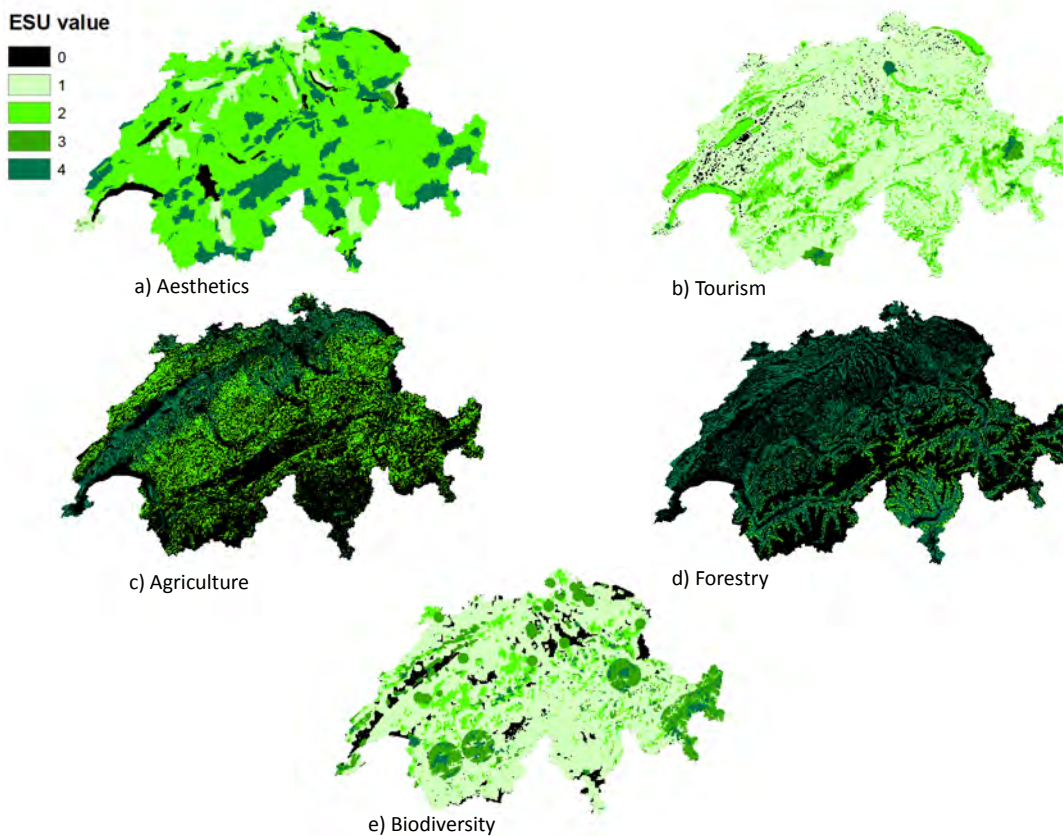


Figure 6: ES values based on conversion from source data. The one legend refers to the same ES values in individual ES maps. a) b) and e) represent data from 2011, while c) and d) are predicted scenarios in 2050.

3.2.7 Edge hexagons

Because the method to overlay a hexagonal grid over Switzerland relies on a fixed point from which to anchor the coverage, the country's irregular borders mean that many of the PU overlap its boundaries. The inset of figure 17 shows some detail of the hexagonal grid along the border of Switzerland. Since the ES analysis was restricted to the country's borders (the data sets not extending to other countries), these hexagons originally held much lower values of ESU due to their smaller coverage within the borders. Assigning this value to these PU would re-

sult in erroneous Marxan outputs since it would preferentially choose these PU with lower ESU values. The true cost of placing a wind turbine on one of these PU would not only affect the area of Switzerland, but also the area beyond its borders. Whether or not this represents an externality is not within the scope of the current study.

To accommodate the border PU, a method was developed in ArcGIS to extrapolate data from surrounding PU. Hexagons selected as suitable wind turbine sites by the previous steps that intersected with the country's borders were isolated manually. A buffer of 1000 m was generated around these 376 hexagons and information about the ESU sum of PU within this buffer was summarised. An average value of ESU was then calculated and assigned as a value to the edge PU. Although this doesn't represent the true ESU value of these PU, it does reflect the overall pattern of ES distribution on the scale of hexagons used in the study. This procedure was repeated for each scenario.

3.2.8 Boundary Length Modifier

The BLM is an optional Marxan parameter that determines how much emphasis is placed on minimising the overall boundary length of the system of selected sites (Game & Grantham, 2008). Minimising this length will create a more compact system of sites. The targets then are more likely to be met in a smaller number of large areas, rather than more smaller collections of sites. In the case of wind turbines, this is an effective parameter as it ensures that wind farms will have a larger minimum number of turbines. This tool, combined with the previous step of limiting the available sites to 3 turbines or more, aim to ensure that economic and practical considerations are involved in the optimisation of turbine locations.

Game & Grantham (2008) outline the method to assign a BLM to the Marxan optimisation. By experimenting with different orders of magnitude of BLM, the appropriate value can be found. This value was used in each Marxan run to encourage grouping of selected sites for wind turbines.

Figure 7 shows an example of how the BLM was calculated. Keeping all other inputs constant, the BLM is changed by several orders of magnitude until a consistent solution that reaches the target is found. Graphically, the point where the curve changes direction is said to demonstrate the correct BLM.

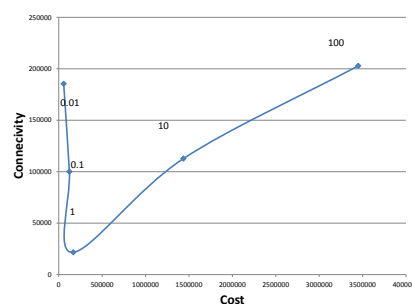


Figure 7: Sample graph of BLM calculations. The BLM value of the points is labeled

3.2.9 Input files used in the present study

The following specifics of each input file used in Marxan outline how the data were modified for this particular use of the program. Samples of these files can be found in the text.

```

Input file for Annealing program.

This file generated by Inedit.exe.
written by Ian Ball and Hugh Possingham.
iball@maths.adelaide.edu.au
hpossing@maths.adelaide.edu.au

General Parameters
VERSION 0.1
BLM 1.0000000000000000E+0000
PROP 0.0000000000000000E+0000
RANDSEED -1
BESTSCORE 1.0000000000000000E+0001
NUMREPS 100

Annealing Parameters
NUMITNS 1000000
STARTTEMP -1.0000000000000000E+0000
COOLFAC 6.0000000000000000E+0000
NUMTEMP 10000

Cost Threshold
COSTTHRESH 0.0000000000000000E+0000
THRESHPEN1 5.0000000000000000E+0000
THRESHPEN2 1.0000000000000000E+0000

Input Files
INPUTDIR D:\Results\Original ESU\Marxan Input
SPECNAME spec.dat
PUNAME pu.dat
PUVSPRNAME puvfeat.dat
BOUNDNAME boundary.dat

Save Files
SCENNAME 12Twh
SAVERUN 2
SAVEBEST 2
SAVESUMMARY 2
SAVESCEN 2
SAVETARGET 2
SAVESUMSOLN 2
SAVELOG 2
SAVESNAPSTEPS 0
SAVESNAPCHANGES 0
SAVESNAPFREQUENCY 23
OUTPUTDIR D:\Results\Original ESU\Marxan output\12Twh

Program control.
RUNMODE 1
MISSLEVEL 1.0000000000000000E+0000
ITIMPTYPE 0
HEURTYPE -1
CLUMPTYPE 0
VERBOSITY 0

```

Figure 8: Example Marxan input file *input.dat* for scenario A, 12 TWh target.

input.dat

The input parameter files were generated using the supplied *inedit.exe* file maker. Most of the parameters were maintained as suggested in Game & Grantham (2008). The number of runs (NUMREPS) was changed to 100 for all analyses. This allows a larger sample of runs to demonstrate the particulars of the different scenarios. 1,000,000 iterations were selected. All runs were conducted with simulated annealing (RUNMODE = 1). An example of this is shown in figure 8.

id	target	spf	name
1	12000000	1	wind Energy

Figure 9: Example Marxan input file *spec.dat* for scenario A, 12 TWh target.

spec.dat

This file was relatively simple, as only one target feature was used in this project. The target id, '1', represents electricity output. 'spf' is an expression of how important it is to reach the target. Since there is only one target, this was set to '1' for all runs in all scenarios. The 'target' was variably set to 5,000,000, 8,000,000, 10,000,000, and 12,000,000 MWh. This unit was used as it avoided decimals while working with the electricity output of PU. The 'name' of the single target used was Wind Energy (figure 9).

pu.dat

The PU identification number (id), as explained earlier, was used to differentiate hexagons. Once the cost of each PU expressed in ESU was calculated using ArcGIS, the values were tabulated versus the potential wind turbine sites and exported as a comma separated values (csv.) file. This was then converted into a .dat file with two columns; id and cost (figure 10).

puofeat.dat

Since there was only one conservation feature explored in this analysis, electricity output, the first column of this file, 'species', was 1. The second column listed the PU id's (pu). The third column was the 'amount' of electricity, in MWh generated by a fictional turbine located on the respective PU. This was one of three values, as calculated earlier, based on the maximum nominal wind speed: 4832 MWh, 6376 MWh, or 7702 MWh (figure 11).

id	cost
3265	168
3270	187
3554	183
3560	196
4134	194
4135	184
4139	237
4140	234
4425	192
4430	178
4431	195
4715	244
4719	200
4720	244
5005	216
5008	175
5010	226
5011	220
5294	160
5297	194
5298	156
5300	254
5301	160
5584	191
5588	174
5589	166
5875	220
5877	220
5878	226
5879	186
6164	236
6165	256
6168	228
6169	264
6453	198
6454	212
6457	184
6458	218
6459	236
6743	201
6748	160
6749	178
7033	214
7037	176
7039	210
7323	206
7329	184
7613	230
7617	176
7618	188
7619	176
7622	160
7907	194
7908	196
7909	184

species	pu	amount
1	3265	7702
1	3270	7702
1	3554	7702
1	3560	7702
1	4134	7702
1	4135	7702
1	4139	6376
1	4140	6376
1	4425	6376
1	4430	6376
1	4431	7702
1	4715	7702
1	4719	7702
1	4720	6376
1	5005	7702
1	5008	7702
1	5010	6376
1	5011	7702
1	5294	7702
1	5297	7702
1	5298	7702
1	5300	6376
1	5301	7702
1	5584	7702
1	5588	7702
1	5589	6376
1	5875	7702
1	5877	7702
1	5878	7702
1	5879	7702
1	6164	7702
1	6165	4832
1	6168	7702
1	6169	7702
1	6453	7702
1	6454	7702
1	6457	7702
1	6458	7702
1	6459	6376
1	6743	7702
1	6748	7702
1	6749	6376
1	7033	7702
1	7037	7702
1	7039	7702
1	7323	6376
1	7329	7702
1	7613	6376
1	7617	7702
1	7618	6376
1	7619	7702
1	7622	7702
1	7907	7702
1	7908	7702
1	7909	7702

Figure 10: Example Marxan input file *pu.dat* for scenario A, 12 TWh target.

Figure 11: Example Marxan input file *puofeat.dat* for scenario A, 12 TWh target.


```

id1, id2, boundary
64103, 63523, 404.145199999213
64103, 63813, 404.14519132622
64307, 64597, 404.14519132622
64307, 64596, 404.145191324357
39995, 40285, 404.145191324357
39995, 39704, 404.145191324357
162511, 161931, 404.145199999213
162511, 162801, 404.145191324357
162511, 162221, 404.145191324357
162511, 163091, 404.145199999213
162799, 162508, 404.14519132622
162799, 162219, 404.145199999213
160191, 160482, 404.145191324357
160191, 160481, 404.145191324357
160191, 159901, 404.145191324357
160191, 160771, 404.145199999213
148562, 148853, 404.145191324357
148562, 148272, 404.145191324357
148562, 148273, 404.145191324357
141296, 141586, 404.145191324357
141296, 141876, 404.145100001246
102694, 102985, 404.145191324357
102694, 102405, 404.145191324357
102694, 102114, 404.145200002939
100310, 99730, 404.145199999213
100310, 100019, 404.145191324357
88194, 88485, 404.145191324357
88194, 87905, 404.145191324357
88194, 87614, 404.145200002939
85582, 85872, 404.145241323351
85582, 85871, 404.145191324357
85582, 85002, 404.145100001246
85582, 85292, 404.145241323351
85582, 85291, 404.145191324357
80935, 81225, 404.145191324357
80935, 80644, 404.145191324357
80935, 80355, 404.145199999213
80935, 80645, 404.145191324357
75979, 76559, 404.145199999213
75979, 76269, 404.145191324357
64014, 64594, 404.145199999213
44606, 44896, 404.145191324357
42262, 42842, 404.145199999213
42262, 41971, 404.145191324357
37550, 37259, 404.145191324357
37574, 37284, 404.145191324357
37574, 37863, 404.14519132622
3554, 3265, 404.14519132622
3554, 4134, 404.145199999213
5008, 5297, 404.145191324357
5008, 5298, 404.145191324357
5008, 5588, 404.145100001246
19496, 18916, 404.145100001246
19496, 19786, 404.145191324357
19496, 19206, 404.145191324357

```

Figure 12: Example Marxan input file *boundary.dat* for scenario A, 12 TWh target.

boundary.dat

This file lists each connection between adjacent hexagonal PU. It shows first the two PU id's (id1 and id2) and the 'boundary length' of the connection between them. Because the PU are hexagonal, each of these connections are of the same value, that is 404.145 m (figure 12).

3.2.10 Scenarios

Marxan was run with the unweighted (original) distribution of ESU calculated by the method described earlier. For each of the four target values (5, 8, 10, 12 TWh) 100 runs of 1,000,000 iterations were used and the 'best solution' and 'selection frequency' were recorded for each.

To test the effect of different values of ES on the optimisation, the ESU value associated with each type of ES was altered in different scenarios. By using ArcGIS to reassign values to each Ha throughout Switzerland, the ESU or cost of individual PU were changed. Additionally, two other scenarios were developed to test the effect of certain restrictions on the optimisation model. The following scenarios were tested using different Marxan runs. The initial assessment was made using the original, unweighted ESU values, whereas the next six scenarios represent

alterations to the ESU valuation. The final two scenarios involve restrictions on available sites:

- A) Unweighted (original) ES assessment
- B) Provisioning services value multiplied by two
- C) Provisioning services value multiplied by four
- D) Cultural services value multiplied by two
- E) Cultural services value multiplied by four
- F) Regulating services value multiplied by two
- G) Regulating services value multiplied by four
- H) Avoiding areas without human infrastructure
- I) Elevation adjustment

3.2.10.1 Restrictive scenarios

Avoiding areas without human infrastructure

Additional scenarios were developed and tested in Marxan in order to test the idea that certain restrictions on the availability of wind turbine sites can affect the optimisation model. It was assumed that wind turbines would more likely be accepted additions to the landscape in areas where infrastructure already exists. The effect of the perception that turbines don't belong in landscapes where there is no preexisting infrastructure was investigated in this part. To test the effect of existing infrastructure on the model, the data set *P32_afg* from the Swiss Landscape Monitoring Program LABES database was used (Kienast *et al.*, 2015). All values of 0, on a resolution of 500 X 500 m, were considered to represent areas where there is no existing infrastructure. Polygons were created based on this information and all potential wind site hexagons that intersected with the areas where infrastructure already exists (the non-0 polygon) were included in a new sample of potential wind sites. This subset of sites was used in further Marxan runs with the original set of ESU.

Elevation adjustment

In their study of the effect of icing on wind turbines in cold climates, Sunden & Wu (2015) show that all of Switzerland is subject to conditions creating ice on wind turbines at least once a year. Much of the country, however, is susceptible to many more days of icing. Swiss alpine areas, in fact, are subject to between 15 and 30 days of these difficult conditions every year. This can have a drastic negative impact on the performance and safety of wind turbines, unless measures are taken to protect them from these conditions (Cattin, 2008). De-icing components are available, but can add considerable cost to a wind power project. Also, maintenance in low temperatures and icing conditions is more time consuming. To mitigate this cost in a financially-responsible environment that will be more appealing to decision makers, elimination of often icing wind turbine sites was conducted in scenario I.

Cattin (2008) shows that icing can occur anywhere in Switzerland at elevations above 1000 m above sea level. Existing sites that are located on exposed ridges and passes are especially susceptible to icing. Because some degree of icing is expected within the mountainous country, the scenario adjustment was not made to this elevation. Instead, a slightly higher 1500 m was selected to allow the program flexibility of choosing some medium altitude sites. Additionally, this would further assess whether altitude differences in ES distribution would have an effect on the optimisation.

By restricting the available wind turbine sites to certain elevations below 1500 m, this idea was tested. This employed ArcGIS to map elevation data for Switzerland. The unweighted ESU distribution of the remaining hexagons was then used in subsequent Marxan runs.

3.2.11 Marxan outputs

The resultant .txt files from each set of Marxan runs was analysed. The *xTWh_best.txt* (figure 13) was imported into ArcGIS and joined to the existing data of potential wind turbine sites. The selected sites were then mapped to visualise their distribution over the Swiss landscape. The associated *xTWh_ssoln.txt* (figure 14) was joined to the existing map of potential sites to demonstrate the selection frequency of each potential wind turbine site. Maps of the best solution and selection frequency of each scenario were then created.

Figure 15 shows the other output file that contains information relevant to boundary lengths and the scores used to calculate the best run.

The best solution represents the run with the lowest cost. It suggests that, for a given electricity output, the particular selection of sites will result in the smallest loss of overall ESU. The selection frequency shows which sites are often included in multiple software runs. Sites that are frequently chosen (more than 75% of the time) are considered *non-negotiable* in that particular arrangement of ES valuation.

3.2.12 ESU loss

ArcGIS was used to determine the amount of each type of ES 'lost' in the resulting Marxan outputs. After isolating the non-negotiable PU in each scenario, the ESU associated with each ES in the respective hexagons was calculated using the summary statistics tool in ArcGIS. The sum of each ES throughout the whole system of selected sites was then calculated and the proportional change versus the original distribution over all potential sites was measured. This change was calculated for each of the four target electricity outputs.

```
"planning_unit","solution"
3265,1
3270,0
3554,1
3560,0
4134,1
4135,1
4139,0
4140,0
4425,0
4430,0
4431,0
4715,1
4719,0
4720,0
5005,1
5008,0
5010,0
5011,0
5294,1
5297,0
5298,0
5300,0
5301,0
5584,1
5588,0
5589,0
5875,1
5877,0
5878,0
5879,0
6164,1
6165,1
6168,0
6169,0
6453,1
6454,1
6457,0
6458,0
6459,0
6743,1
6748,0
6749,0
7033,1
7037,0
7039,0
7323,1
7329,0
7613,1
7617,0
7618,0
7619,0
7622,1
7907,0
7908,0
7909,0
```

```
"planning_unit","number"
179385,0
179096,0
178805,0
178225,0
178224,0
177935,0
177064,0
176781,0
176774,0
176490,0
176484,0
176483,0
176201,0
175910,0
175909,0
175904,0
175620,0
175619,0
175329,0
175324,0
175040,0
175039,0
174754,0
174749,0
174744,0
174463,0
174457,3
174456,0
174455,0
174174,0
174173,0
174172,0
174167,3
174161,1
173885,0
173884,0
173883,0
173877,3
173876,0
173594,0
173593,0
173592,0
173587,3
173586,0
173581,1
173305,0
173304,0
173303,0
173291,1
173014,0
173013,0
173012,0
173003,8
173000,1
172725,0
```

Figure 13: Example of Marxan output file 12TWh_best.txt for scenario A, 12 TWh target.

Figure 14: Example of Marxan output file 12TWh_ssoln.txt for scenario A, 12 TWh target.

Run_Num	Score	Cost	Planning_Units	Connectivity	Connectivity_T	Connectivity_L	Connectivity_E	Connectivity_C	Connectivity_I	Penalty	Shortfall	Missing_V	MPPM
1	460746	413461	1816	47284.987	14109113	890331.85	47284.987	13171496	0.063103	0	0	0	1
2	477949.3	421369	1845	56580.327	14109113	869720.44	56580.327	13182812	0.061642	0	0	0	1
3	484904.4	433578	1853	51326.44	14109113	895585.74	51326.44	13162201	0.063476	0	0	0	1
4	479097.3	428175	1848	50922.293	14109113	862849.98	50922.293	13195340	0.061156	0	0	0	1
5	474670.3	424860	1851	49709.858	14109113	872145.32	49709.858	13187258	0.061814	100.4278	810	1	0.999933
6	475648.3	427555	1842	48093.277	14109113	881440.65	48093.277	13179579	0.062473	0	0	0	1
7	472476.7	418681	1845	53751.31	14109113	878207.49	53751.31	13177154	0.062244	44.38659	358	1	0.99997
8	469202.5	421013	1839	48093.278	14109113	876995.06	48093.278	13184024	0.062158	96.21227	776	1	0.999935
9	459874.6	413802	1817	46072.552	14109113	884673.82	46072.552	13178366	0.062702	0	0	0	1
10	471794.6	422893	1835	48901.568	14109113	889119.42	48901.568	13171092	0.063017	0	0	0	1
11	477057.7	422094	1844	54963.746	14109113	873357.75	54963.746	13180791	0.0619	0	0	0	1
12	489062.6	428845	1846	60217.634	14109113	868508.01	60217.634	13180387	0.061557	0	0	0	1
13	474595.2	420436	1846	54155.455	14109113	873761.9	54155.455	13181195	0.061929	3.719547	30	1	0.999997
14	467846.4	421727	1828	46072.552	14109113	836176.4	46072.552	13226864	0.059265	46.86629	378	1	0.999969
15	482410.2	432616	1860	49709.859	14109113	853150.49	49709.859	13206252	0.060468	84.30972	680	1	0.999943
16	468652.9	416114	1838	52538.874	14109113	889927.71	52538.874	13166646	0.063075	0	0	0	1
17	478950.7	434790	1870	44051.826	14109113	877399.21	44051.826	13187662	0.062187	108.8587	878	1	0.999927
18	477322	427208	1841	50114.004	14109113	872549.46	50114.004	13186449	0.061843	0	0	0	1
19	467318.1	419629	1844	47689.132	14109113	876186.77	47689.132	13185237	0.062101	0	0	0	1
20	472336.9	423025	1838	49305.712	14109113	868103.86	49305.712	13191703	0.061528	6.199244	50	1	0.999996
21	475848	431392	1850	44455.971	14109113	870124.59	44455.971	13194532	0.061671	0	0	0	1
22	462250.6	409710	1832	52538.875	14109113	885886.25	52538.875	13170688	0.062788	1.735788	14	1	0.999999
23	480384.8	420486	1826	59813.488	14109113	890331.85	59813.488	13158967	0.063103	85.3016	688	1	0.999943
24	469892.7	416524	1842	53347.165	14109113	888311.13	53347.165	13167454	0.06296	21.57337	174	1	0.999985
25	474692	424161	1839	50518.149	14109113	876995.06	50518.149	13181599	0.062158	12.89443	104	1	0.999991
26	470210.3	419288	1830	50922.294	14109113	864466.56	50922.294	13193724	0.06127	0	0	0	1
27	470244.5	413260	1845	56984.472	14109113	884673.82	56984.472	13167454	0.062702	0	0	0	1
28	491985.5	432172	1845	59813.488	14109113	868912.16	59813.488	13180387	0.061585	0	0	0	1
29	461686.7	412381	1828	49305.713	14109113	879015.79	49305.713	13180791	0.062301	0	0	0	1
30	463949.9	420269	1831	43647.68	14109113	845471.73	43647.68	13219993	0.059924	33.22795	268	1	0.999978

Figure 15: Example of Marxan output file 12TWh_sum.csv for scenario A, 12 TWh target.

3.2.13 Assumptions of the model

In Marxan, the costs associated with a PU are traded off with the target feature gained from using that area for another purpose. In the current model, the ESU are considered lost when the PU is selected as a wind turbine site. As such, it is assumed that when a site is selected, all the ESU associated with that hexagon will no longer be available. In other words, the true cost of selecting a site for wind electricity production is the total ESU of a hexagon with an area of 554,256 m². This is the worst case scenario where all ES are incompatible with wind turbines. This is unrealistic, however, as the services provided by the area around a wind turbine will be variably affected by its construction, operation, and disassembly. The resolution of the wind potential analysis is much higher than the hexagons and so it is assumed that a wind turbine can be constructed anywhere within a PU in order to make the best use of available wind.

4 Results

4.1 Wind Turbine Locations

The selection of possible wind turbine sites based on wind potential and wind speed resulted in 18,446 PU for the original assessment over all of Switzerland. The distribution of these hexagons is shown in figure 16. It seems that the majority of large clusters of sites are on the Central Plateau and in the Jura mountains, with more scattered groups lying within the area of the Alps.

The available sites for wind turbines were used throughout scenarios A through G. The two modified setups, however, limited the number of available sites for the analysis. These resulted in a different number of PU since restrictions were made on certain areas in Switzerland. Scenario H incorporated 16,150 PU or available sites while scenario I used only 9,712.

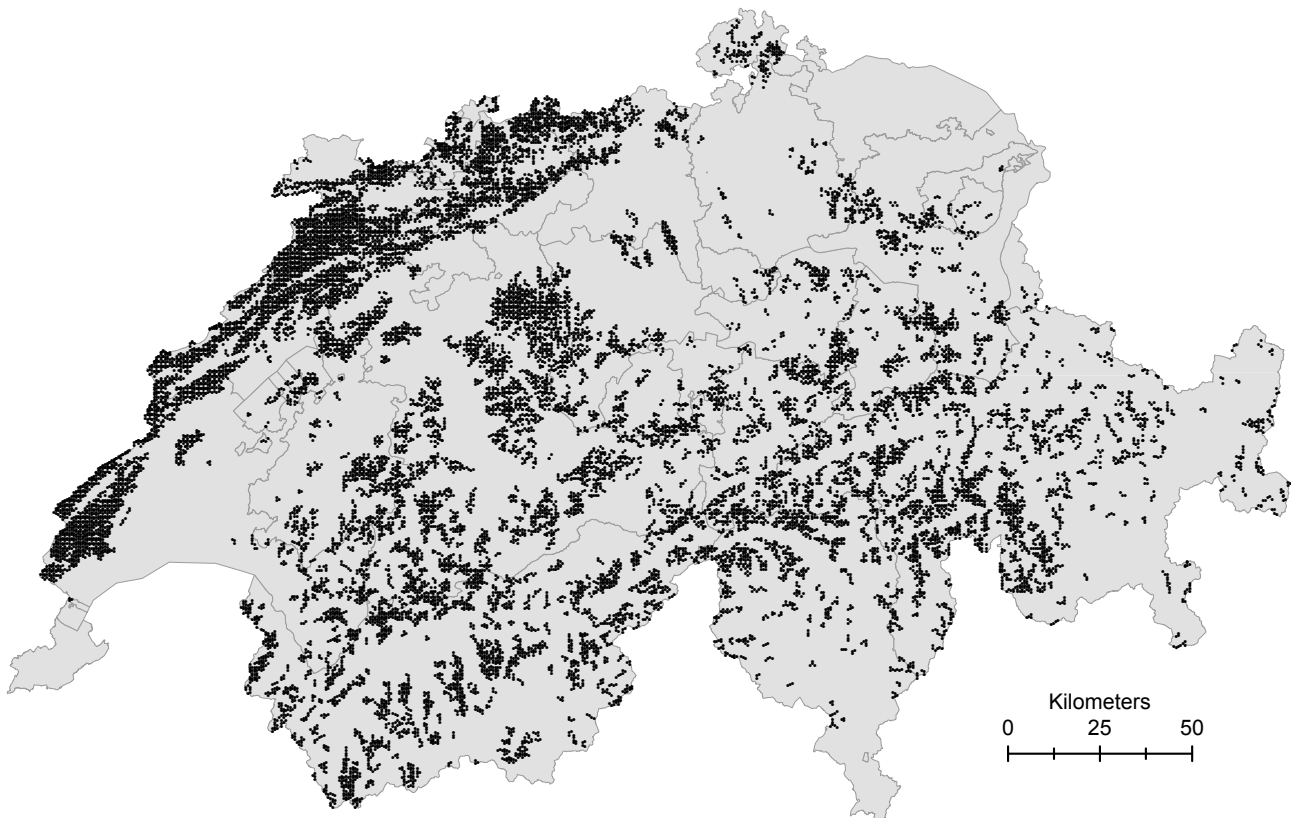


Figure 16: Location of hexagons representing available wind turbine sites aggregated to groups of three or more.

4.2 Electricity Output

Figure 17 shows the theoretical amount of electricity generated by a single turbine of the supplied specifications at each of the possible locations. The inset on

this same figure shows how the distribution of wind speed at a height of 120 m relates to each of the hexagonal PU that was included in the analysis. It is important to emphasise again that only a small fraction of a hexagon's area need contain suitable wind in order for it to be included as a possible PU. Additionally, the model assumes that at least one turbine can be installed in a selected PU. In reality, more turbines could be built, pending local conditions. This would increase the electricity output, thereby reducing the required number of PU used to reach a given target. In the present study, however, this 'worst case scenario' situation was used. These parameters could be modified in a repeated study.

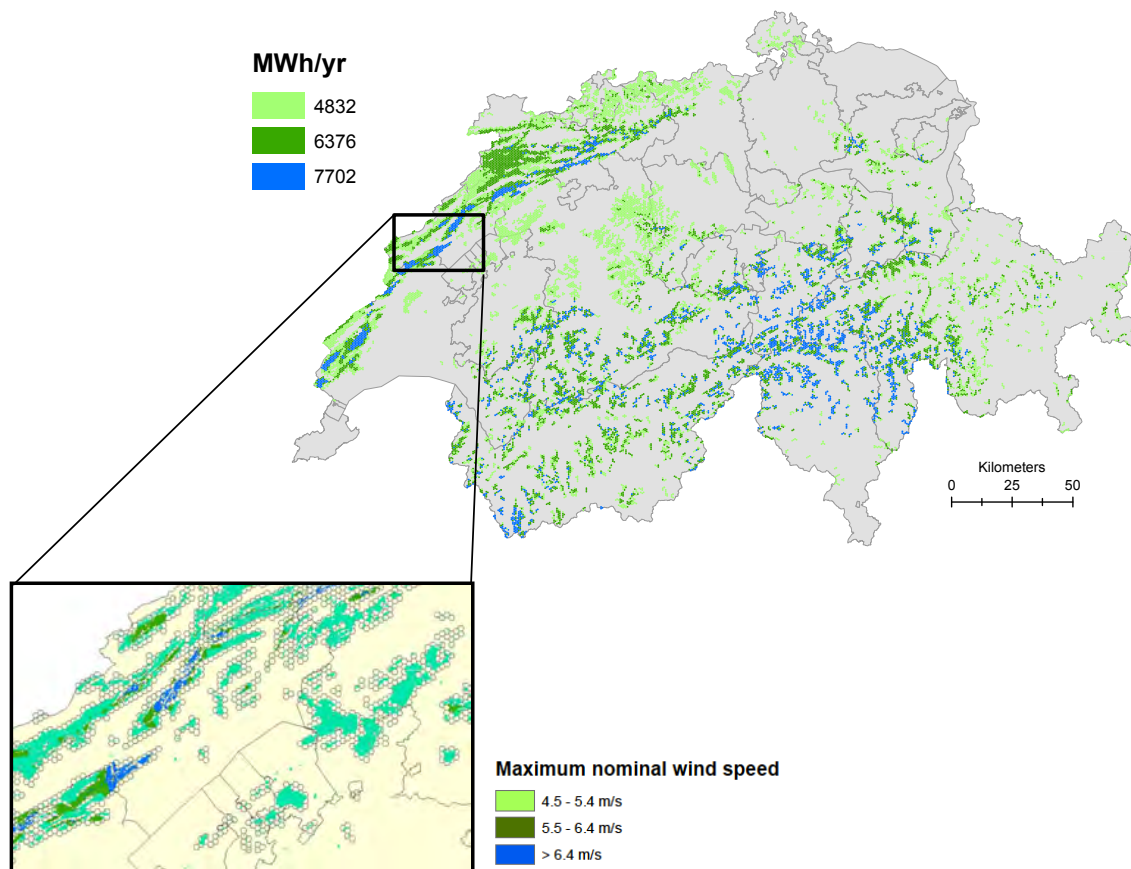


Figure 17: Distribution of theoretical electricity output generated by a turbine placed on each PU. The inset shows a closeup of PU and their associated wind speed used to calculate the electricity output.

4.3 ESU

The distribution of the combined, unweighted ESU calculated on a Ha scale over all of Switzerland is shown in figure 18. This is the result of summing ESU values from each of the five ES (aesthetic, tourism, agriculture, forestry, and biodiversity) as described in the methods. It is evident that the distribution of these services is not uniform across the landscape. Some areas are lower in overall ESU, such

as the Central Alps, whereas the Plateau contains very high values. In general, alpine valleys have more ESU than the surrounding mountaintops. Most of the water bodies within the country have very low associated ESU.

Each scenario tested in this project incorporated a certain distribution of ESU over the possible wind turbine locations. The distribution of ESU in the original set of values over these sites is shown in figure 19. Summed ESU for hexagonal PU are between 40 and 667 units. This reflects a subset of ESU distribution over the entire country and emphasises the differences mentioned above.

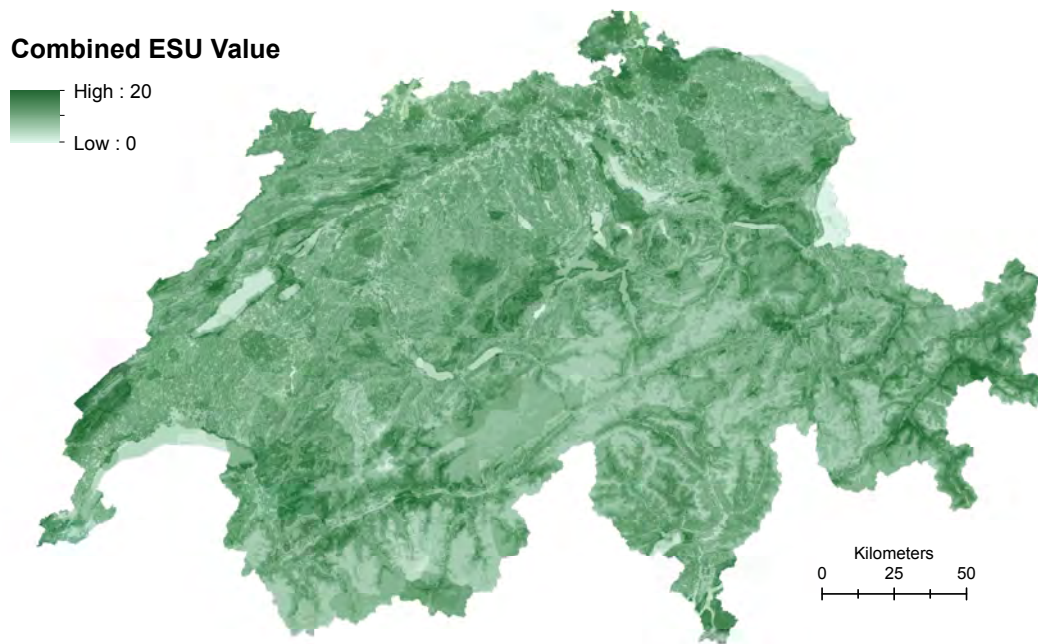


Figure 18: Distribution of combined ESU over Switzerland as calculated for the un-weighted scenario A.

4.4 Scenarios

A) Unweighted ESU

The initial runs of Marxan were conducted using the first set of unweighted ESU derived from the source data. Figure 21 shows the resulting best solutions for all four target electricity outputs along with the number of PU included in the solution. In general, most of the chosen sites are in the Central and Southern Alps. Some sites are located in the Jura and Plateau, but these seem to be less numerous. As the target is increased, the number of chosen turbine sites in the Alps increases, while a few more sites are located in the lowlands. There is a general trend toward concentrating more selected sites in the mountains as the output is increased. Although the number of sites varies through the different outputs, there doesn't seem to be a noticeable difference in the distribution of these sites. It is important to note that the 'best' solution is only somewhat representative of the results. More relevant to this study are the selection frequencies, as follows.

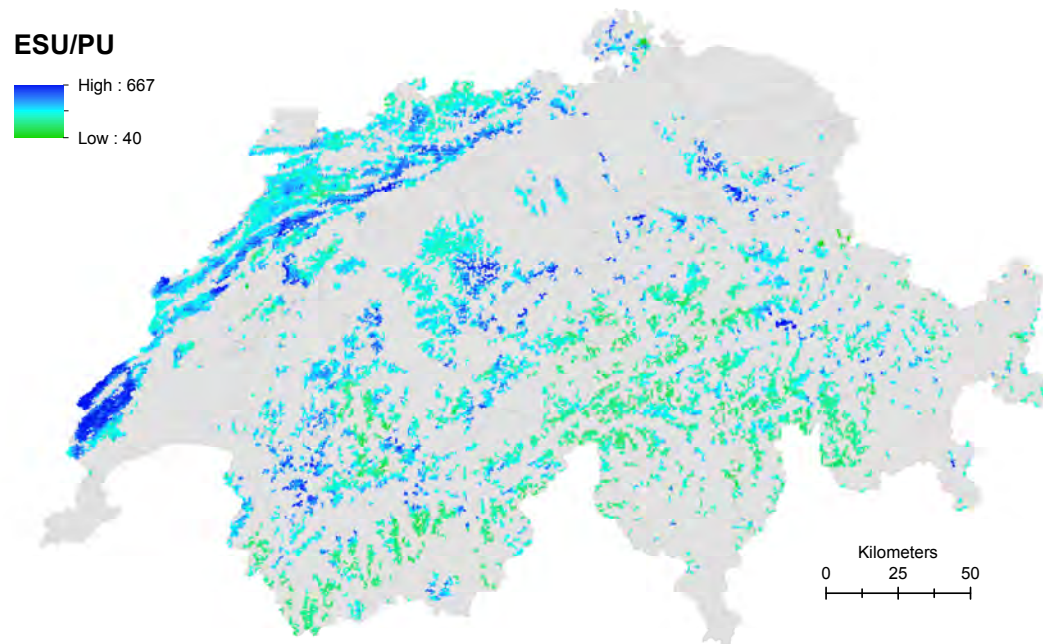


Figure 19: Distribution of combined unweighted ESU over potential wind turbine sites.

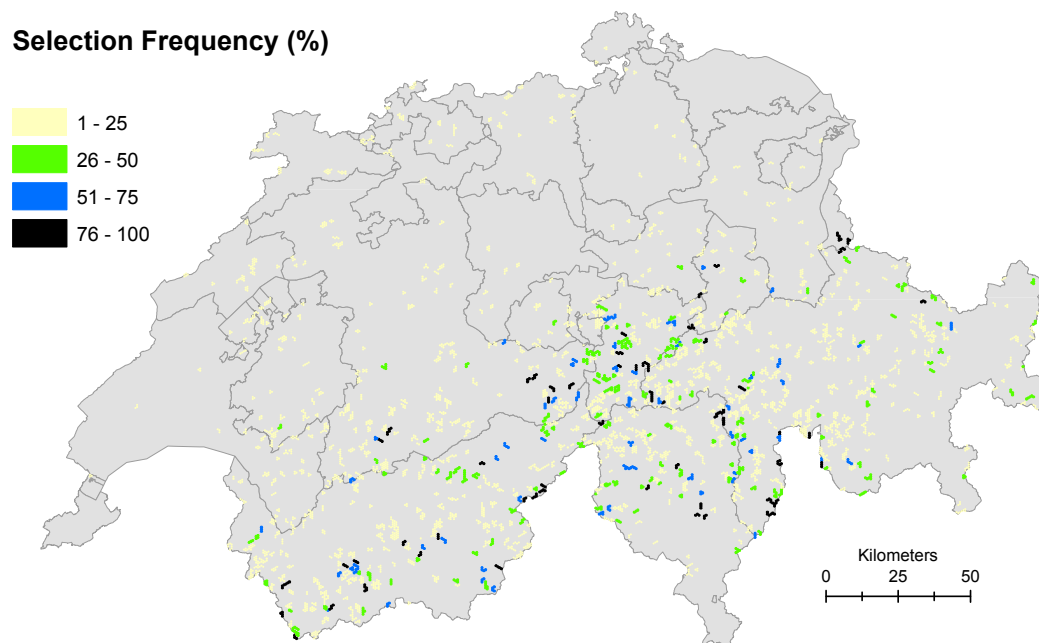
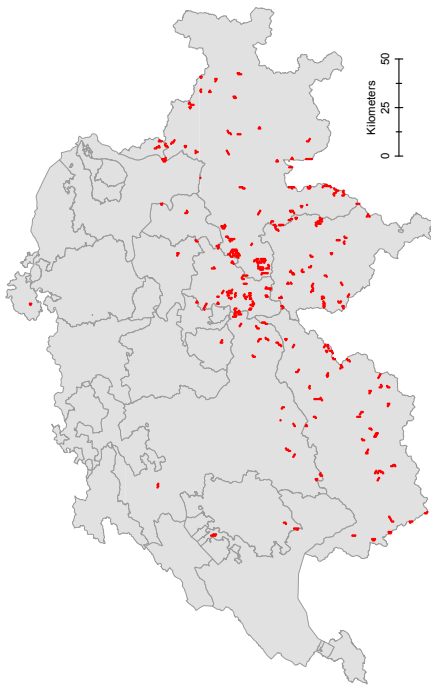
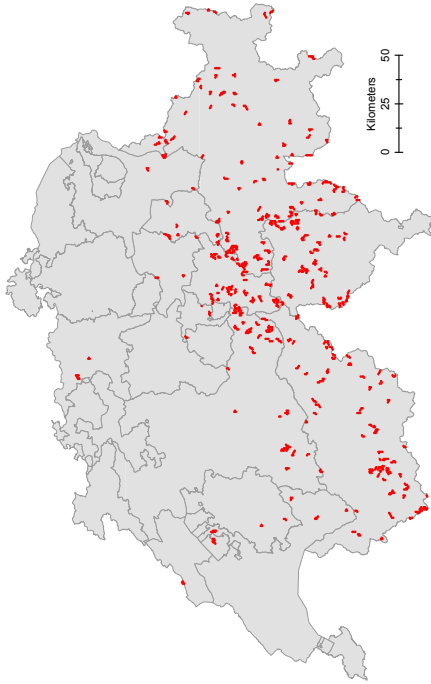


Figure 20: Selection frequency of wind turbine sites by Marxan in the unweighted scenario A, with a 5 TWh target.

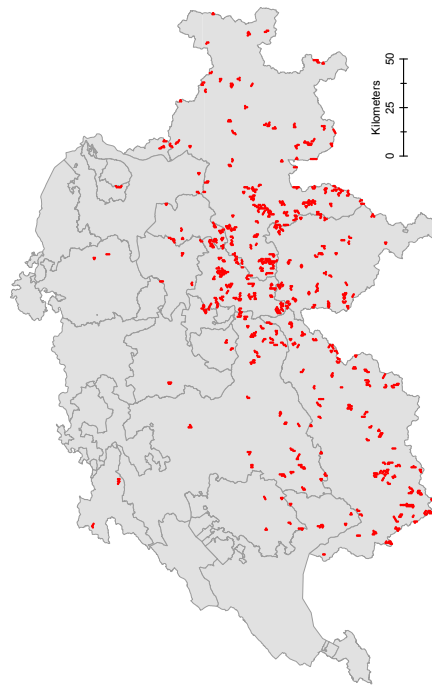
Figure 20 shows the frequency of site selection over all of Switzerland as a result of the Marxan analysis using the unweighted ESU distribution and a 5 TWh target.



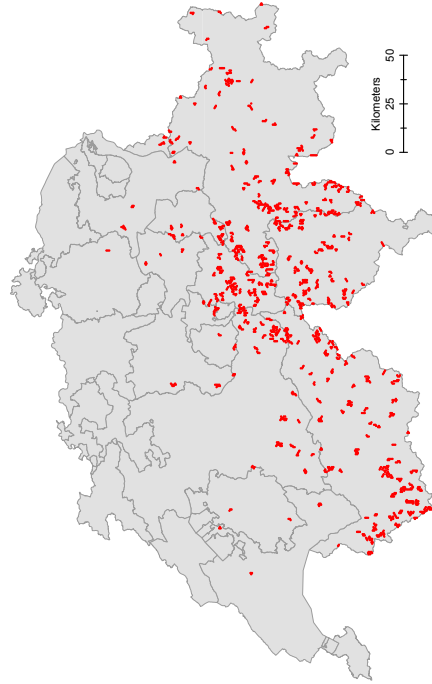
(a) 5 TWh target. 751 turbine sites selected.



(b) 8 TWh target. 1,210 turbine sites selected.



(c) 10 TWh target. 1,512 turbine sites selected.



(d) 12 TWh target. 1,815 turbine sites selected.

Figure 21: Marxan best solutions for Scenario A (unweighted) over four targets. Chosen wind turbine locations are indicated by red dots. Each caption also indicates the number of sites selected to reach the target.

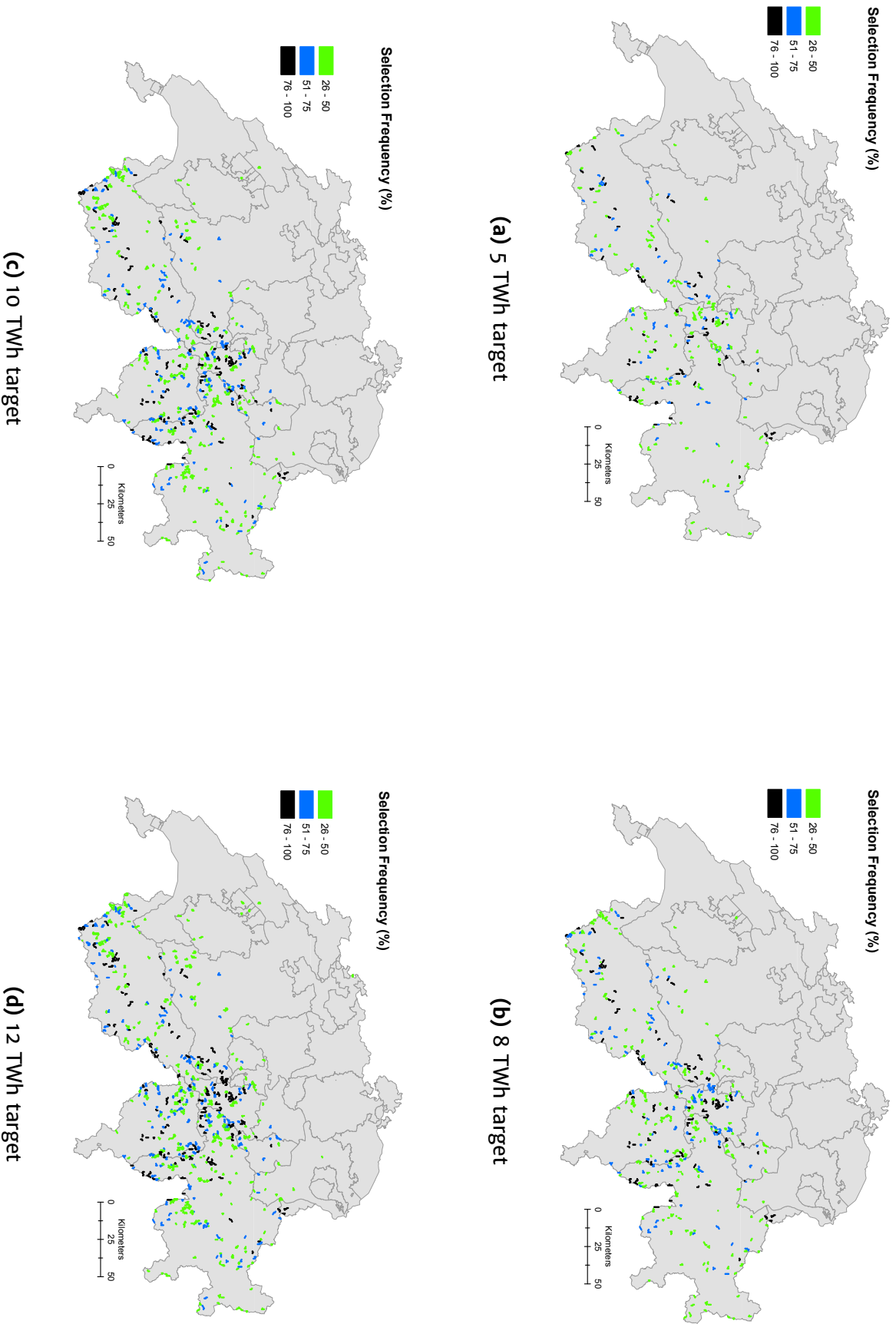


Figure 22: Selection frequencies of potential turbine sites chosen by Marxan for the original unweighted scenario A over four targets.

This demonstrates that, although many sites are chosen at least once over the 100 runs, few sites are chosen relatively often (more than 25% of the time). This shows that the optimisation program is indeed selecting various combinations of PU and testing them as solutions. These less often chosen sites are scattered around the whole of Switzerland. Although it is difficult to confirm, sites chosen less than 25% of the time tend to be in areas separate from those that are chosen more often. The selection frequencies of individual potential turbine locations across the four different target outputs resulting from analysis with Marxan are displayed in figure 22. In these instances, only sites that have been selected at least 25% of the time are displayed.

In all of the original ESU scenario analyses, the vast majority of sites chosen with a high frequency are located in the area of the Northern, Central, and Southern Alps. Figure 22d shows an example of this pattern.

B) Provisioning services multiplied by two

Figure 23 shows the frequency distribution of the resultant Marxan analysis with a 12 TWh target in the doubled provisioning service value scenario². There is a clear emphasis on sites in the Alps region, not unlike that found in the original ESU assessment. What differs, however, is the lower number of high frequency, or non-negotiable sites. Compared to figure 22d, there are fewer of these often chosen sites. Marxan chooses sites with less consistency in this scenario.

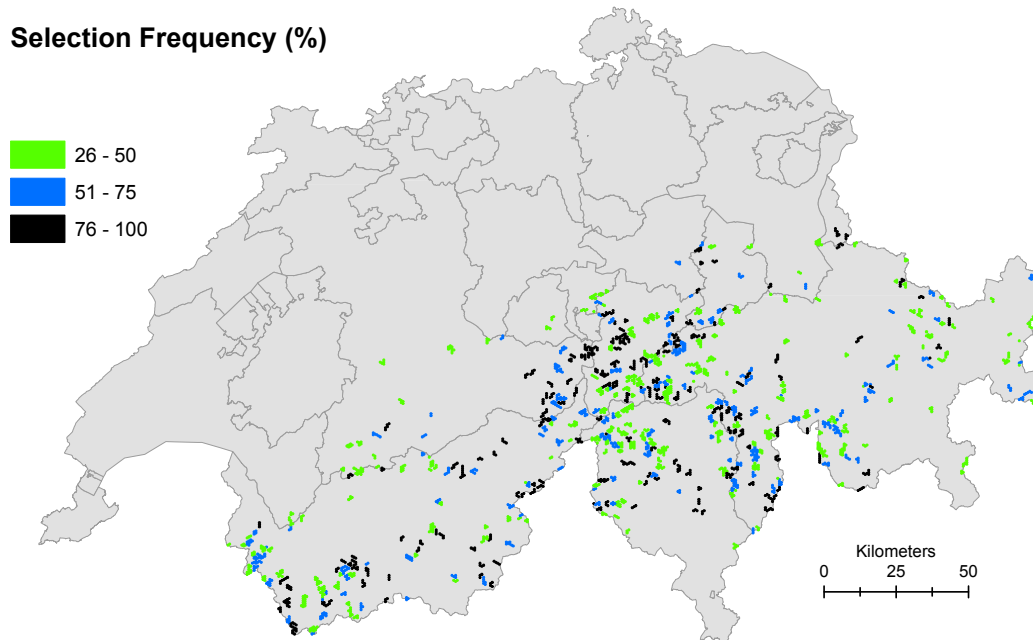


Figure 23: Selection frequency of wind turbine sites by Marxan in scenario B, with a 12 TWh target.

²For the complete results of Marxan analyses for each scenario, please refer to the appropriate letter in the appendix (appendices B through I)

C) Provisioning services multiplied by four

This scenario resulted in a clear preference for turbine sites located in the alpine region. There are no sites within the lowlands or plateau that are selected more than 25% of the time (figure 24). Clearly there is a preference for these sites in the southern part of Switzerland.

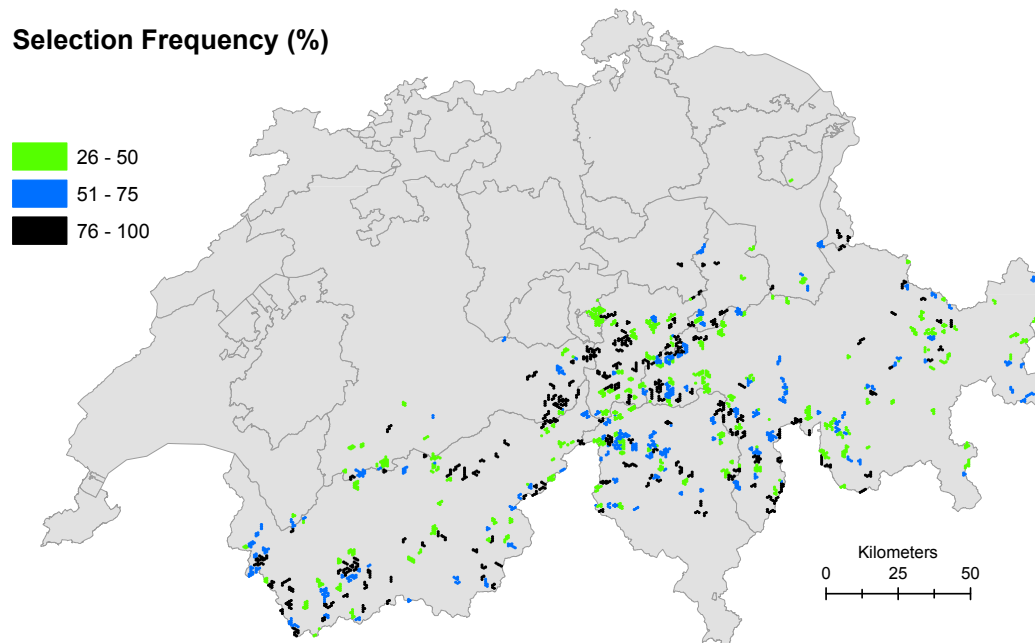


Figure 24: Selection frequency of wind turbine sites by Marxan in scenario C, with a 12 TWh target.

D) Cultural services multiplied by two

When landscape services are emphasised in the Marxan analysis, the general pattern of preference for sites in the Alps is maintained (figure 25). Similar to scenarios B and C, there seems to be a relatively small number of non-negotiable sites compared to the initial analysis. There is a noticeable change, however, in that in this case, sites in the medium-elevation canton of Bern are chosen more frequently than in A, B and C.

E) Cultural services multiplied by four

Figure 26 shows how Marxan chooses sites when the landscape services are emphasised further. There is a continuation of the selection of sites in Bern and a noticeable lack of sites in the Plateau or Jura when compared with the initial analysis. When compared with results from B and C, less sites in the Eastern part of Switzerland have also been selected with a high frequency.

Selection Frequency (%)

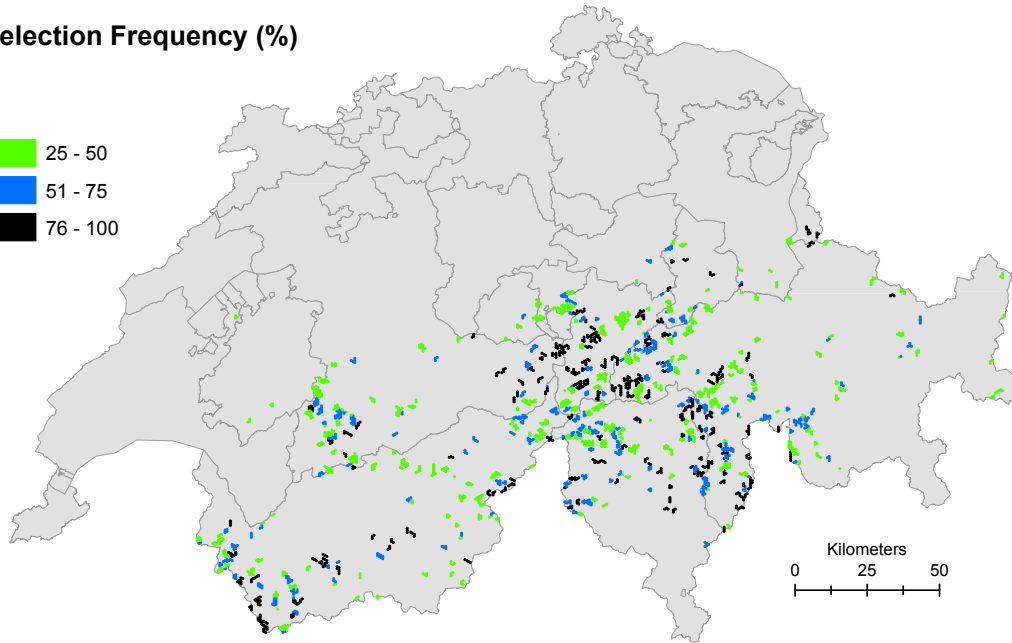
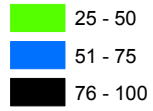


Figure 25: Selection frequency of wind turbine sites by Marxan in scenario D, with a 12 TWh target.

Selection Frequency (%)

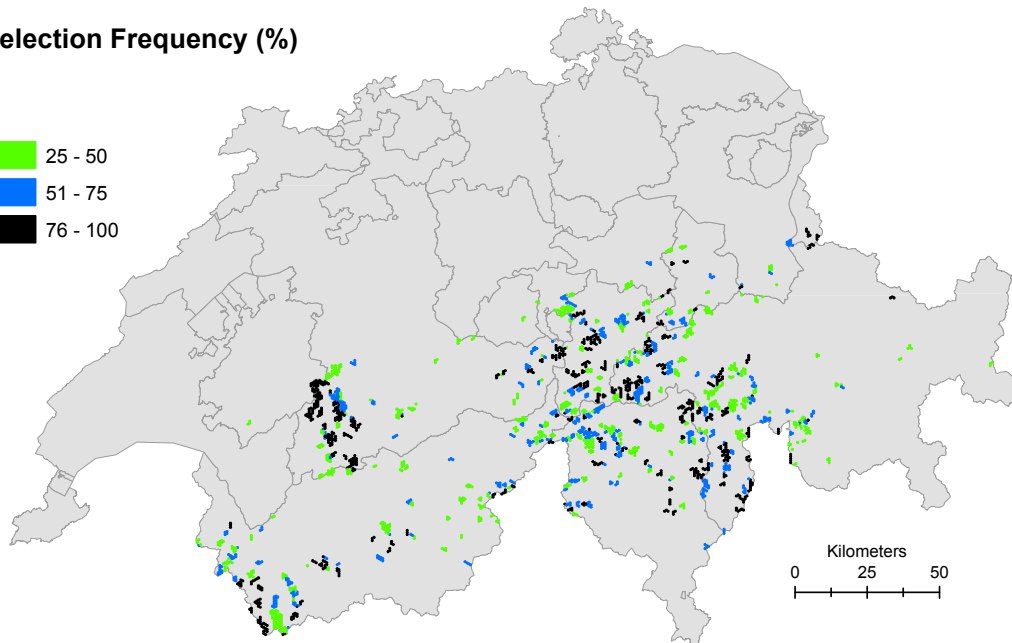
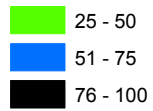


Figure 26: Selection frequency of wind turbine sites by Marxan in scenario E, with a 12 TWh target.

F) Regulating services multiplied by two

When biodiversity value is emphasised, a slightly different pattern emerges from the Marxan optimisation (figure 27). Some sites in the Plateau are selected and there seems to be a slightly higher number of high frequency (non-negotiable) sites in the results. Otherwise, the output is similar to what has been seen so far, with the Alps regions being preferred, particularly areas in the Northern Alps. Sites on the sides of valleys in the south are also emphasised.

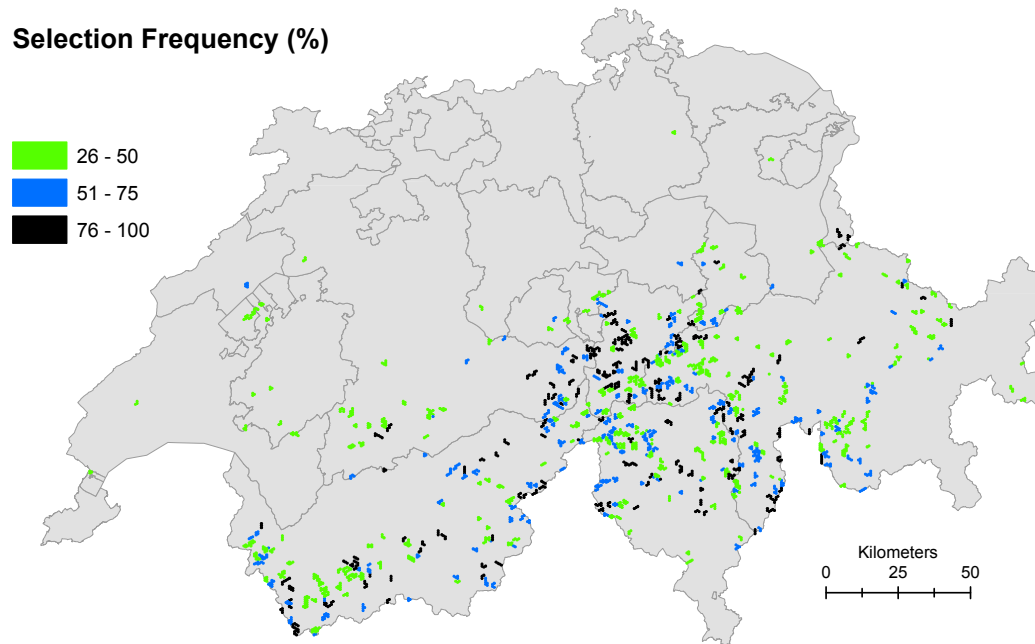


Figure 27: Selection frequency of wind turbine sites by Marxan in scenario F, with a 12 TWh target.

G) Regulating services multiplied by four

Figure 28 shows an extension of the pattern seen in scenario E. There are very few sites selected in the canton of Bern and in the east, unlike in D and E, and even more high frequency sites in the Plateau. Here, the non-negotiable sites have again increased in number.

H) Areas without human infrastructure

Sites that were located in areas where no previous infrastructure exists were excluded from this model scenario. Here, only 16,150 sites were available for wind turbines. Figure 29 shows areas in Switzerland where infrastructure already exists. Most of the PU that were excluded from this analysis were in the higher elevation Alps where the landscape is relatively free of infrastructure. The resulting distribution of sites selected by Marxan seems to have been slightly affected by this change in available sites. Figure 30, for instance, shows the selection frequency

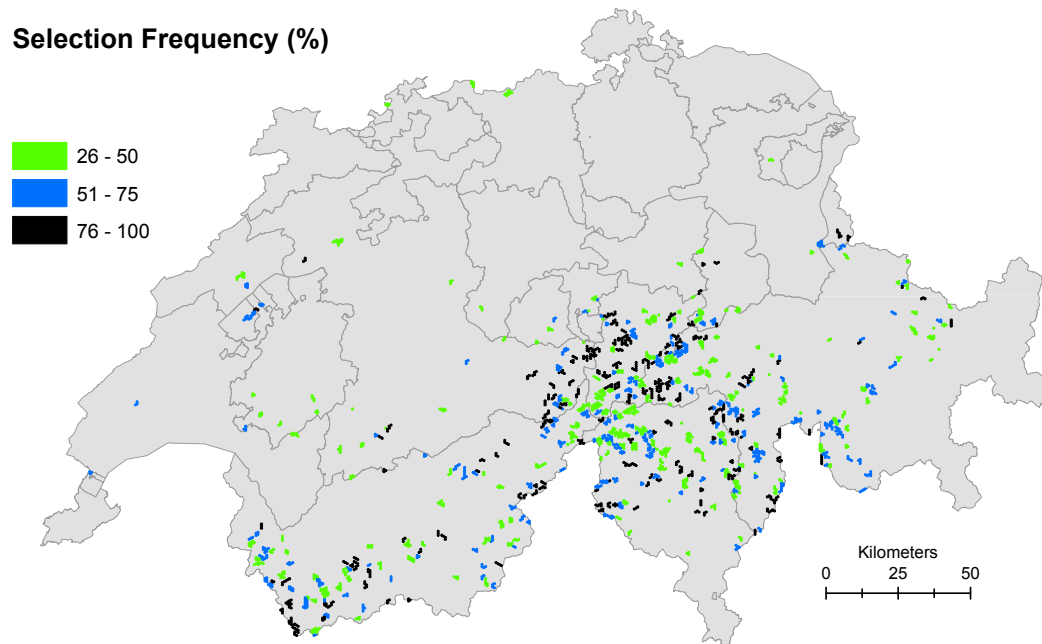


Figure 28: Selection frequency of wind turbine sites by Marxan in scenario G, with a 12 TWh target.

of sites in the Landscape Perception analysis using the original ESU distribution and with a 12 TWh target. By comparing this to Figure 22d, we can see some minor differences in the distribution of sites in the mountains.

Overall, there isn't a discernible change in distribution of selected sites when the lack of existing infrastructure is introduced as a constraint in the optimisation analysis.

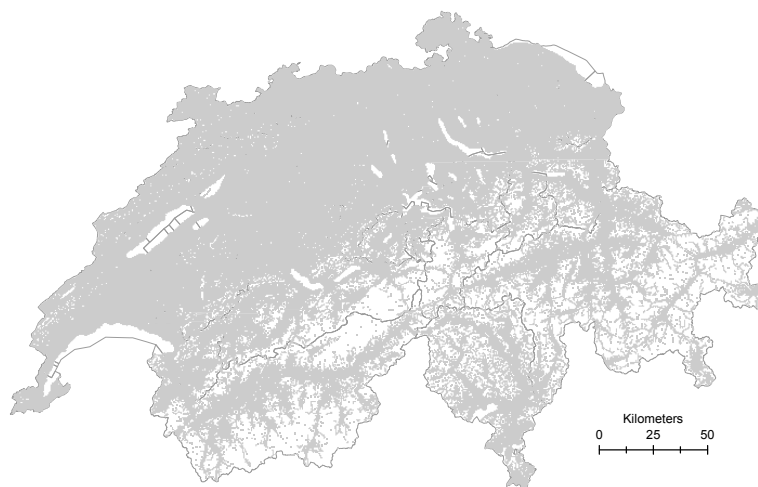


Figure 29: Areas of Switzerland with existing infrastructure. Unshaded areas of the map are free of infrastructure.

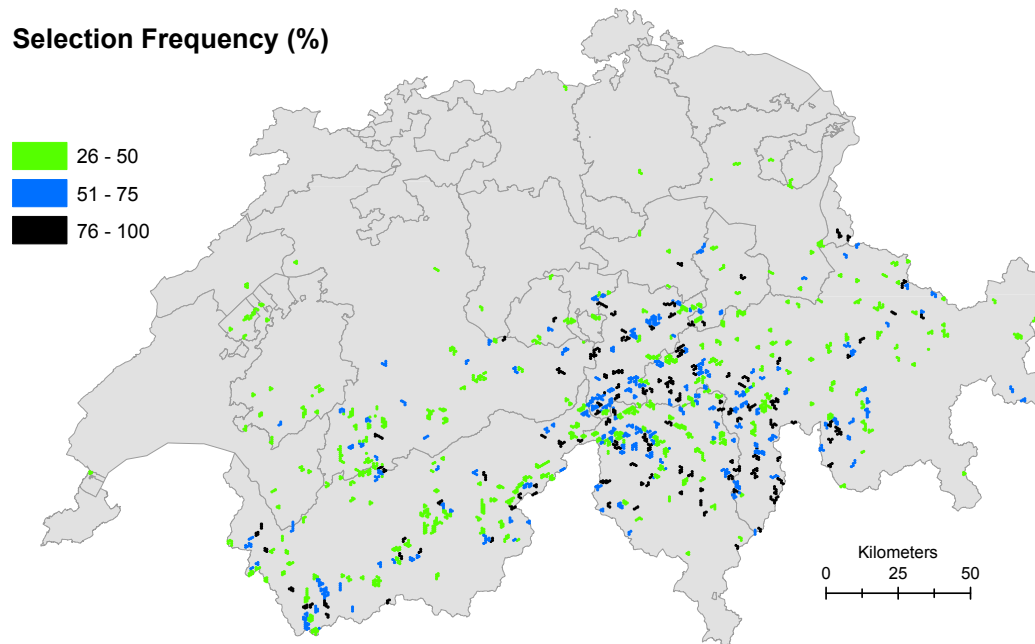


Figure 30: Selection frequency of turbine sites by Marfan in the scenario H, with a 12 TWh target.

I) Below 1500 m

Many high altitude sites were excluded from this scenario. Only 9,712 potential wind turbine sites were available in this part of the study and the resulting Marfan optimisation differed from the original analysis. Figure 31 shows the selection frequency distribution from the original ESU scenario with a 12 TWh target in this case. When compared with figure 22d, there is a notable difference in the sites chosen. In the elevation-restricted model, sites in the lowlands are chosen more frequently than similar areas in the other scenarios. This pattern is reflected in the results from runs with all target values.

Virtually no sites were chosen in the Alps regions, with the vast majority of sites selected in Plateau and Jura. Some medium elevation areas in Bern and surrounding cantons were chosen very frequently. Much of the lowlands is covered in sites that were chosen with relatively high frequencies. Here, there seem to be a large number of sites selected in more than 25% but less than 50% of runs.

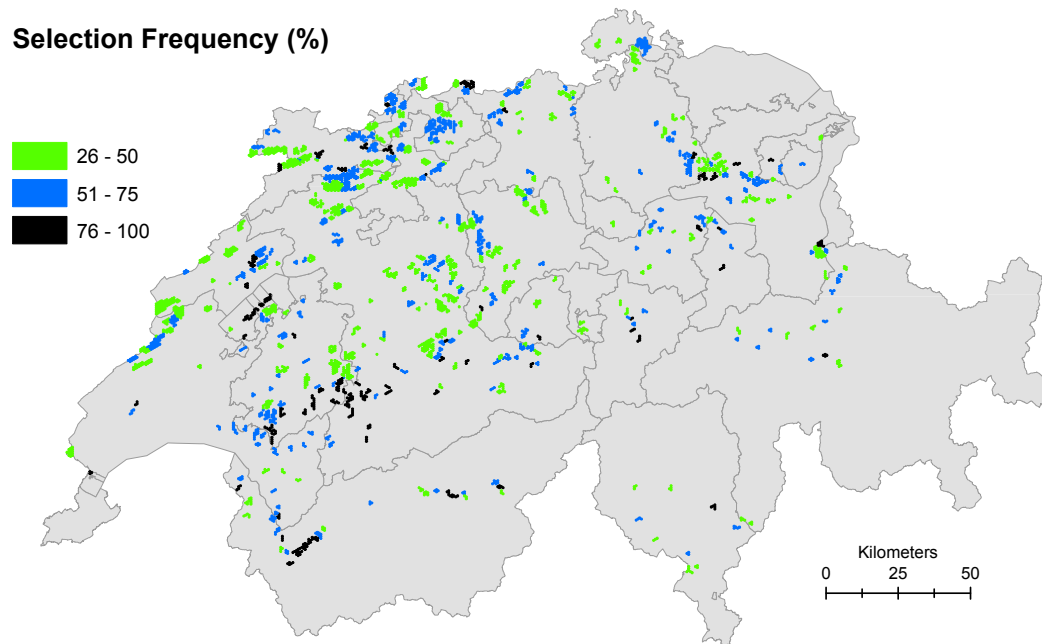


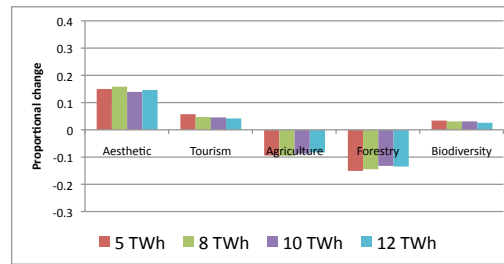
Figure 31: Selection frequency of wind turbine sites by Marxan in scenario I, with a 12TWh target.

4.5 ESU Loss

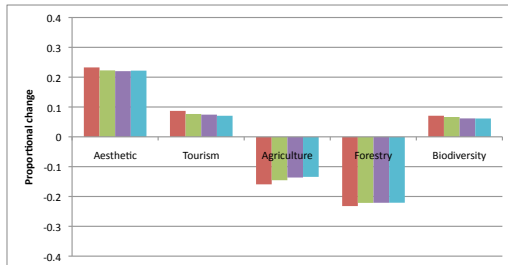
The amount of each ES that was affected by solutions offered by Marxan in each scenario was investigated. Each of the scenarios was tested this way in order to better understand two things. First, it was used to demonstrate that the program actually offers unique optimisation solutions for each scenario and that it is balancing trade offs in an effective way. Second, the analysis served to demonstrate that one can better understand the patterns of ES over a landscape and their vulnerability to wind electricity production by examining the ESU loss.

Figure 32 compares the amount of ESU lost by each ES due to a theoretical wind turbine being constructed at non-negotiable sites. The proportional change in each ES lost versus its initial distribution in the particular scenario is graphed. If the cost of the system of selected sites involved the same proportion of ESU of a given ES as in the initial distribution over all available sites, then the proportional change would be zero. Positive values indicate that the particular ES 'suffered' proportionately higher losses in terms of ESU than would be expected if site selection was random. Negative values indicate that the particular ES 'suffered' proportionately lower losses in terms of ESU than would be expected if the selection of sites was a random sample from the available turbine locations.

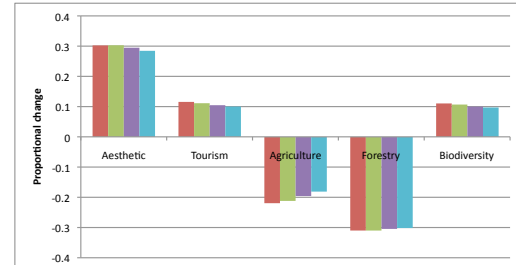
Figure 32a suggests that, under initial conditions, Marxan preferentially chooses sites that result in more cultural services being lost, along with regulating services, than provisioning services. In other words, the areas in which turbines are suggested to be built are more valuable in terms of cultural and regulating services. When figures 18 and 22d are considered, it is clear that the area in the Central Alps where most of the non-negotiable sites are located are low in ESU. Further, figure 18 shows that agriculture and forestry are especially sparsely rep-



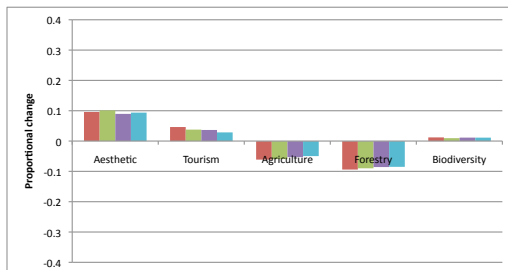
(a) Unweighted ESU [A]



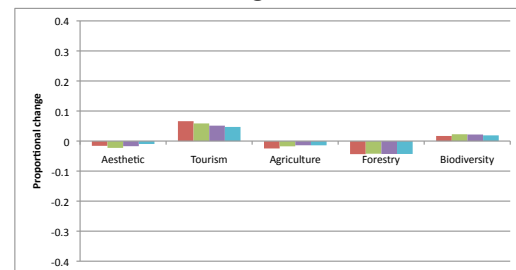
(b) Provisioning services X 2 [B]



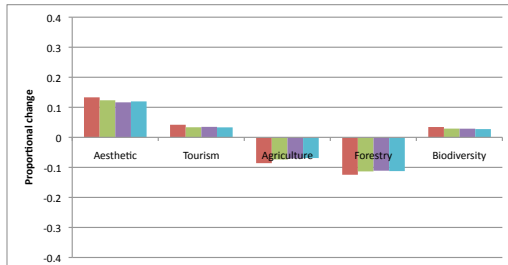
(c) Provisioning services X 4 [C]



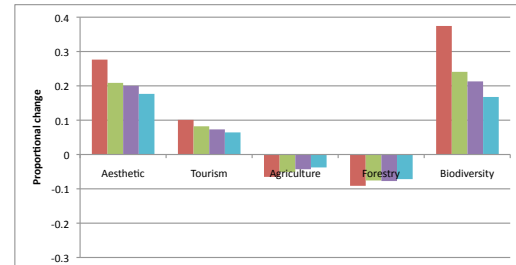
(d) Cultural services X 2 [D]



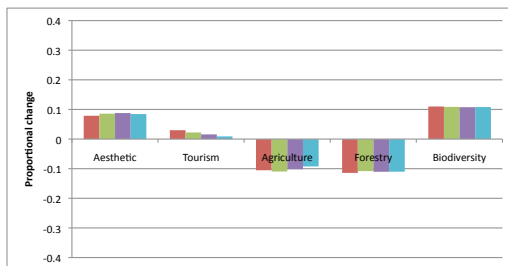
(e) Cultural services X 4 [E]



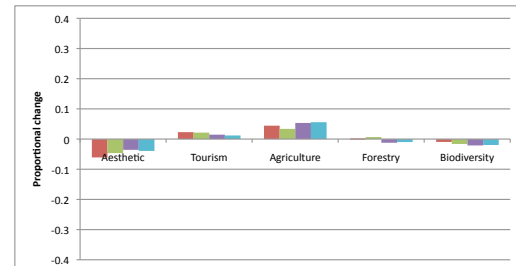
(f) Regulating services X 2 [F]



(g) Regulating services X 4 [G]



(h) Infrastructure limited [H]



(i) 1500 m restriction [I]

Figure 32: Proportional change in ESU lost versus the original distribution in each scenario across all targets resulting from optimisation with Marxan. The legend in (a) refers to all graphs. Scenario designations are in square brackets. Zero proportional change: the same ratio of ESU from different ES was lost in a particular scenario as was in the starting distribution over available sites. Positive values: indicate that the particular ES 'suffered' proportionately higher losses in terms of ESU than would be expected if site selection was random. Negative values: indicate that the particular ES 'suffered' proportionately lower losses in terms of ESU.

resented in that area. When the available turbine sites are limited by landscape perception, the pattern of ESU loss is generally the same (figure 32h), although more biodiversity units are lost. Figure 30 shows that the selected sites are not in different areas than in the original assessment. When the altitude limitation is introduced, however (figure 32i), the disparity in loss between the different ES groups is basically eliminated. Sites that are selected in the lower elevations (figure 31) tend to have more evenly distributed ES.

The increase in value of provisioning services in scenarios B and C produces a more exaggerated difference between these and cultural services that are lost in Marxan's solutions (figures 32b and 32c). Emphasising provisioning services results in them being lost in much smaller proportions than cultural services.

When cultural services are given greater value (figures 32d and 32e) the difference between the distribution of ESU lost over all ES groups and the original distributions is much smaller. Here, the selected sites are still in the mountainous region (figures 25 and 26), and so increasing the value of cultural services that are found there doesn't greatly change the outcome of the Marxan runs, but influences the distribution of ESU loss.

By increasing the value of biodiversity as an ES, a less clear pattern emerges (figures 32f and 32g). Again, the amount of cultural services loss is greater than the amount of provisioning services lost relative to the initial conditions. However, there is a notable increase in biodiversity ESU loss when its value is quadrupled.

5 Discussion

Marxan was originally designed as a conservation planning tool. In the present study, it was successfully applied to a land-based optimisation exercise to suggest solutions for the trade off between ES and wind electricity production in Switzerland. This study demonstrates that, by changing the value of ES in the analysis, the optimisation program responds differently as the ES trade off patterns across the landscape change. This suggests that Marxan weighs the trade offs and offers unique solutions to the different scenarios. Figure 32 shows that different scenarios produce different patterns of ESU loss. Changing the target output within each scenario does not seem to affect these patterns, meaning the program successfully balances the entire cost with a system wide target output. Additionally, increasing the target output value in each scenario increased the number of sites chosen in a solution (figure 21), suggesting that the program was reacting to these changing parameters. These results demonstrate the successful adaptation of a methodology to apply Marxan to the present study.

5.1 ES valuation in a wind electricity optimisation analysis

The problem of ES evaluation and valuation has been hotly debated (Busch *et al.*, 2012). This will be an ongoing theme in research as scientists and decision makers develop new techniques to understand the provisioning of services by the ecosystems on which we depend. This study did not deal directly with this issue. Instead, I am concerned with the proper use of this carefully-gathered data toward supplying good information to decision makers.

By using predetermined values for ES, the costs of building wind turbines in the Swiss landscape can be evaluated. Using this as input for a Marxan optimisation analysis allows for proper comparison of costs. Orsi *et al.* (2011) used cost maps that incorporated weighted ES. This is similar to what was done in the current study with the various scenarios. I experimented with different weighting schemes of ES that produced different ESU combinations for use in Marxan. These altered patterns of ES value generally affect the program's output, reflecting different trade off scenarios. This supports the idea that proper ES valuation is critical to understanding the relationships on a system wide scale. In the end, it is the responsibility of the decision maker to place weight onto the value of ES, whereas science can evaluate ES based on these criteria and make recommendations for minimising ES loss through optimisation programs such as Marxan.

In this study, arbitrary ESU were used to value and compare services. These units can be adjusted to suit the needs of the user. Monetary amounts could easily be incorporated and so there is additional flexibility in the model.

Although this study did not focus on how to evaluate ES, it allows for better understanding of the way that they are affected by changes in a management plan. To do this involves the ecology behind the provisioning of ES (Bennett *et al.*, 2009). Most ES studies relating land cover to ES assume a linear relationship between ecosystem structure and the provisioning of services. This has been shown to be untrue, however, and the sensitivity of various ES to wind farms can differ (Bennett *et al.*, 2009; Grilli *et al.*, 2013). Because the ES value is determined before input into Marxan, the program is free to make an objective evaluation based

on the provided data. Different ES sensitivities to wind electricity production can be built into the model before the optimisation is conducted. Also, Marxan allows for the different evaluation of ES at different scales (Broekx *et al.*, 2013) which resolves some of the issues here.

5.2 Evaluating trade offs between wind electricity production and ES - what are the costs?

Many studies have examined the conflicts between renewable electricity production and ES. This is the first to quantify the relationship between ES and wind electricity on land using an optimisation approach. By defining the cost as ESU lost when a PU is selected as a turbine site, the model demonstrates the worst case scenario of interaction between ES and wind electricity. In other words, the interaction is assessed as possessing a very high level of conflict, so much so that the ES are no longer provided by the landscape. Although not entirely realistic, this method was used to illustrate the applicability of the program in this instance. The results show that *Marxan does indeed evaluate trade offs* between ES and wind electricity production by selecting sites that result in the lowest amount of lost ESU in a given run. The amount of conflict in this study is equated with the ESU lost. Thus we can, given a proper set of data with decision maker-evaluated ES, generate least conflict solutions for ES and wind electricity generation problems.

Marxan output, when analysed, shows that some areas of Switzerland are much more suited to low-impact wind electricity generation than others. This is similar to what was found in other studies (Hergert, 2013; Hergert *et al.*, 2014; Segura Morán *et al.*, 2014; Huber *et al.*, 2015). In the present study, however, the trade off can be quantified. As already mentioned, the program's power lies in its ability to preferentially choose the least costly, high output sites over more costly, low output ones. The non-negotiable sites are the result of this pattern. To evaluate the cost of this trade off, the amount of ESU lost (conflict) can be calculated.

To actually *evaluate* the costs to the entire system, Marxan provides a total for each solution of each run. Figure 15 shows the output file that contains this information in the 'Cost' column. This represents a sum of all ESU lost over all the hexagons that were selected in each individual solution. For instance, the first run of scenario A with a 12 TWh target output resulted in 413,461 ESU lost. All other runs had a similar value. The sums from this model are from an arbitrary assignment of ES value and so the cost can only be interpreted in the context of the chosen parameters. In a real application of this software, however, this total cost would be invaluable for providing management advice.

When interpreting Marxan outputs, it is integral to recall that best solutions are simply one of many possible outcomes. By interpreting the selection frequency results, we can get a better understanding of the optimisation patterns. Especially interesting are the non-negotiable sites that are generated in each run of the program. These can be used to identify areas that are most likely to be beneficial in minimising trade offs between wind electricity production and ES provided by the landscape.

Spatially-explicit conflict maps have been generated for renewable electricity production (including wind) in the studies previously mentioned. Areas of high

conflict included much of the Jura and southwestern Plateau areas of Switzerland. These are also areas of high wind electricity potential (Hergert, 2013; Segura Morán *et al.*, 2014). In most of the scenarios explored in this study, Marxan tended to not choose sites in that area. This suggests that the cost of placing turbines at those sites outweighs the benefits of the high wind potential. Only when the higher elevation sites were excluded was the pattern changed significantly (see results of scenario I, figure 31). Almost all of the non-negotiable sites in scenario I were located in the Plateau and Jura. With ES mapped as they were in this study, the lower elevation sites incorporate more total ESU than those in the alpine valleys and in the mountains.

In addition to learning more about broader ES patterns and trade offs with wind electricity production, the effects of a system of wind turbines on particular ES within the analysis can be evaluated (see figure 32). This is a great step forward in the application of conflict analysis in the case of wind electricity generation. Theoretically, if a monetary value was attributed to ES used in the Marxan analysis, a combined amount of lost ES expressed in monetary terms could be extracted. Then, the contribution of individual ES to this loss could be easily extracted from the resulting data. This is the sort of information that policy makers would be able to consider when making spatial planning decisions.

5.3 Advantages of using an optimisation approach to balance the loss of ES and benefits of wind electricity production in Switzerland

Segura Morán *et al.* (2014) assessed the potential wind electricity production with varying degrees of ES conflict in Switzerland. By selecting only sites with low ES conflict coupled with medium or high wind electricity potential to produce 5 TWh of electricity in their assessment, they found that 1,027 turbines were needed. In the present study, only 751 sites with at least one turbine were found to be needed for the *same electricity output*. This suggests that the same output can be achieved with 25% less turbines if an optimisation approach to planning is used.

There are several explanations for the difference in turbine number between the two analyses. First, Segura Morán *et al.* (2014) selected potential wind turbine sites following the procedure described in Lütkehus (2013). Here, they traced a point grid along the suitable areas and chose points with the *highest* wind speed and traced a 500 m buffer around them. This means that areas with lower average wind speed, although theoretically suitable for electricity production, were not always considered in their model. Using hexagons in the present study allows the landscape to be systematically divided and provides flexibility in turbine location on a local scale. In their subsequent conflict analysis, Segura Morán *et al.* (2014) used sites with “high” or “medium” wind potential, meaning some of the sites with lower wind speeds weren’t used in the study. Second, the previous study used a much smaller turbine footprint than the present one, meaning that there was potential to place more turbines in a given area. A 500 m buffer suggests a radius of 250 m from the turbine site, whereas I used a radius almost double that. Third, the ES studied were not evaluated in the same manner, although some of the source data was shared between the two studies (such as aesthetics and tourism potential). This potentially leads to different areas of conflict and different sites to be chosen. The first two differences would suggest that the

model built by Segura Morán *et al.* (2014) would result in a smaller area required to produce the same electricity output. However, this is not the case. The major difference lies in the way that Marxan operates.

The heuristics used by Marxan to test different combinations of solutions aims for the lowest costs for an overall output. This process selects sites that have the highest output in terms of electricity generation potential and balances this with ES loss. The sites with high output and lowest costs will therefore be selected first. Since the large scale distribution of ES in this analysis shows little small scale variability, neighbouring sites would then have been selected since they would presumably also have low associated costs and high benefit. Once most of these sites were selected, other high output sites with medium associated costs would then be selected along with medium output and low cost sites. Next the medium output, medium cost sites are chosen. Finally, if required, low output and low cost sites are then added to the resulting system. This pattern ensures that the 'best' or most productive sites in terms of electricity production, coupled with lowest ES cost, would be used first. By closely examining the progression in figure 22, this pattern of site selection can be seen; windy sites in the mountains are first selected, then, as the target is increased, clusters start to form in these areas. Then, more windy sites in nearby mountainous areas are selected. Finally, more clusters appear around these and the earlier selected sites.

Successfully evaluating and interpreting the trade off between electricity production and ES loss is critical in the development of a spatial plan that incorporates different electricity sources. The characteristic of Marxan to first choose the "cheap" sites with greatest output sets it ahead of other methods to model the spatial planning of wind turbines in the landscape. By offering solutions with a lower number of turbines than the one other similar study shows that using the present method can drastically reduce the suggested amount of electricity infrastructure needed to solve Switzerland's future energy dilemma.

5.4 What Marxan tells us about ES in Switzerland

The results of this analysis allow us to make some additional observations regarding ES across the Swiss landscape in this case. By examining the results of the ESU loss, some patterns emerge. Figure 32a, b, c, d, and e show that the sites selected in the higher elevations are more rich in cultural services than the other classes. When provisioning services are made more valuable, the proportional changes are not altered significantly. This means that the sites being chosen do not host many of these services. Conversely, increasing the worth of cultural services doesn't greatly change the pattern of selected sites (figure 25 and figure 26) but the effect on ESU loss is clear. Cultural services, weighted more, are lost in about the same proportion that they are represented in the overall distribution. Therefore, the mountainous areas are lower in provisioning services and higher in cultural services. This can be seen in an examination of figure 6, where much of the alpine areas have zero or low provisioning ES. This pattern is not surprising, given the lack of high altitude farming in Switzerland. Hastik *et al.* (2015), in their broad assessment of ES, found that the Alps are high in cultural ES. They also found that there was high wind potential on mountain ridges, peaks, and passes, echoing the findings in this study.

Scenarios H and I both restricted the number of higher altitude sites available for

the Marxan analysis. Being forced to choose sites on the Plateau and in the Jura, Marxan helps to demonstrate that the ES are more evenly distributed across these areas. Figure 32h and figure 32i suggest that the ES are consumed in the non-negotiable sites in similar proportions to the starting distribution. The program doesn't seem to consistently select any ES more than others. This shows that the lower elevation sites tend to have a wide array of ES associated with them. Figure 6 reinforces this observation.

These observations of ES are only particular to the evaluation conducted in this study. It may not be a reflection of the true state of ES in the Swiss landscape, but it does allow us to examine patterns that emerge. The same could be done for a more realistic analysis with other data.

5.5 Wind electricity as part of the renewable energy mix in Switzerland

This study, combined with those that have preceded it, shows that the development of renewable electricity sources (including wind) in Switzerland is a complex affair that requires careful attention. Spatial planning is already a much-studied topic in the country and has resulted in some important advances in the field. Applying these concepts to the changing energy supply will aid in the effective development of renewable sources as nuclear energy is phased out over the next thirty years. Although Switzerland's goals are ambitious, these studies show that there is promise in the country's renewable electricity potential.

The present study shows that ES trade offs with wind electricity production can be evaluated and managed to select optimal turbine locations, even when the worst case scenario is assumed (that all ES around a turbine will be lost). This type of assessment will be critical in ensuring the effectiveness and societal acceptance that is necessary for renewable electricity sources to succeed in the mix. Wind power especially is dependent on public support (Todt *et al.* , 2011), and towards this goal, local impacts must be mitigated with system-wide benefits. The landscape service approach is accepted in Switzerland at the cantonal and confederation level (Segura Morán *et al.* , 2014) and so using tools, such as Marxan, to apply these concepts in order to better inform decision makers is paramount.

5.6 Further advantages of Marxan and the ES approach

The assessment and integration of the ES approach in Marxan presents a holistic view of the system being assessed. By involving more than one ES, we can get a clearer picture of patterns on various spatial scales. There is almost no limit to the number of costs (in this case, ES) that can be incorporated in the program and so complicated systems can be analysed. In this case, an abiotic output was used to evaluate trade offs with ES. Other services or outputs, based on the CICES system of classification could easily be incorporated. Ecosystems are often made of complex interactions that may be difficult or impossible to fully comprehend. Marxan, however, simplifies this approach as the interactions between each and every ES does not have to be known. Instead, we simply require an understanding of how these services relate to the target output. In this study, the real effects of wind electricity generation on ES were not fully known, but the overall model

structure remains consistent. Once the costs are known or approximated, the program can be used to assess the trade offs between these in order to find an optimal solution. This is important for communication with decision makers because for spatial planning, it is the sum of interactions that is important when policy decisions are to be made. Individual components can be weighted beforehand, allowing for a subjective assessment to be interpreted in an objective environment.

A good example of the flexibility of the model developed here toward incorporating various ES at different spatial scales regards the perception of landscape beauty. The aesthetic effects of wind turbines on landscape perception have been well documented in many situations, but public perception seems to vary on the issue (Leung & Yang, 2012). The visual impact of wind turbines isn't necessarily restricted to local scales. Turbines seen from a distance can also affect cultural ES value from afar. These effects would not be localised and so would have to be properly incorporated into a model. In the present study, the PU created were larger than the recommended size for wind turbines, as already discussed. A further advantage of this technique is that the cultural ES effects are distributed over a larger area, reflecting the real situation. Further, by restricting the available sites to those that are free of human infrastructure in scenario H, I attempted to account for public perception in the acceptance of wind turbines in the landscape. Parameters could be modified to adjust for these effects once they are evaluated and quantified in a study area. Additionally, using GIS to prepare the data beforehand would allow for different costs on different scales to be incorporated into the model.

The problem of a mismatch in scales has hampered other attempts to investigate the optimisation of electricity systems in other studies (Howard *et al.*, 2013). The local and regional impacts of electricity production are poorly understood, while the social effects of ES changes are normally considered at a large scale. Marxan addresses this issue by enabling variable inputs. The user can define the cost to different ES across differing scales, so long as that cost is expressed on the appropriate PU scale. This allows the impacts of changes to the energy system configuration to be identified for different areas, increasing the chances of decreasing land use conflicts.

It has been shown that temporal changes should be addressed in the ES approach (Bolliger *et al.*, 2011). Some studies have explored this idea by mapping changes over time and in different future scenarios. In the present study, some of the ES data included were obtained from future scenarios (Price *et al.*, 2015), whereas others are from current landscape patterns. This shows that Marxan allows for temporal changes to data to be incorporated into the model. This is important as it can then be used to help develop a flexible spatio-temporal analysis framework in which changes to the energy system configuration can be identified for specific areas (Howard *et al.*, 2013).

Marxan incorporates many user-defined settings that allow for flexibility in the model developed in this study. If a planner was not concerned with the size of wind parks, based on the number of turbines, then the BLM could be ignored. If certain sites were already designated as wind turbine locations, then these PU can be 'locked' in for each run. This allows for the integration of the program into existing spatial plans. Segura Morán *et al.* (2014) incorporated extant wind farms

in their analysis and the same could be done using Marxan.

5.7 Limitations of Marxan and the present model

Marxan uses algorithms to find the least costly sites in a solution. This doesn't necessarily mean that it is finding sites that have lower overall conflict. It could be that those particular sites are low in some conflicts between ES and wind electricity production, but high in others. It is possible that the chosen sites still represent a conflict between ES, but it just so happens that it is the least costly of these relationships. The program doesn't distinguish why it chooses a particular site over another. We can only evaluate the amount of ES lost in each site and across the entire system, without clearly understanding the reasons behind their inclusion in a Marxan solution. This may be difficult to communicate to a decision maker who wishes to know why a particular site is chosen. The optimisation treats the system as a whole, diluting the effects of single sites and masking individual selection criteria.

One major drawback of simplifying the conflict between ES and electricity production by reducing it to a trade off is that additional costs are often missed. For instance, transaction costs and management costs should be incorporated into a realistic model ES analysis (Makino *et al.*, 2013). However, adjusting the model setup can address this problem. Götz (2014) incorporated the cost of setting up conservation areas into the Marxan model. Göke & Lamp (2012) include a variety of costs in their model, including variable costs for infrastructure related to the construction and maintenance of offshore wind turbines. As such studies show, some of these costs can be incorporated using the method outlined in this study.

The quality and reliability of data represents another great limitation of using an optimisation program to assess ES trade offs (Göke & Lamp, 2012). Uncertainty in the calculation or evaluation of ES will result in outputs that may not truly reflect the real world situation. The results of the optimisation also depend heavily on the definition of targets and the translation of the potential conflicts into parameters used.

Some of the model assumptions may affect the outcome of the optimisation. For example, the large hexagons used for PU in this study are not realistic as the suggested distance between wind turbines is much smaller. However, as was discussed earlier, justification lies in the flexibility that this approach offers. If a PU was considered suitable for wind turbines, this actually represents the potential for multiple sites to be used within this area. By assessing this PU as being suitable for just one turbine, I am analysing a worst case scenario. This means that a real situation could result in greater output for the same amount of cost (by supplying more electricity through more turbines without reducing the supply of other ES further).

5.8 Future possibilities

Marxan is possibly the most used conservation planning tool in the world (Götz, 2014), but it is not the only one. Recently, a more sophisticated version of the software has been introduced. Marxan with Zones (Watts *et al.*, 2009) is an extension of the same program, but it allows more than the binary option for a

given PU designation. Instead, the program tests for potentially unlimited uses of a PU. This way, the new program can explicitly address multiple objectives (eg. social, economic, ecological) in a systematic way. It provides a framework with which to evaluate the consequences and trade offs of alternative zoning configurations. This is critical for informed decision making.

Most of the studies conducted up until now that use Marxan with Zones are conservation related, but there are clear potential applications in spatial planning and renewable energy production (Klein *et al.* , 2009). In the latter case, Marxan with Zones could be applied to test for more than one type of electricity production on a given site. For example, it could evaluate trade offs between using an area for wind or for solar electricity production and offer solutions with a mix of these sources. This would build on the ideas presented by several studies that explore ES conflict with other types of renewable electricity in Switzerland (Hergert, 2013; Segura Morán *et al.* , 2014). To do this, an alternate zone for rooftop solar panels would be added, the potential extent of which has already been calculated by Hergert (2013). Different targets for each type of electricity source could then be assigned so that a certain level is maintained in the entire system (Watts *et al.* , 2009; Wilson *et al.* , 2010).

Marxan with Zones has a few other features that improve on Marxan if used to examine the optimisation of electricity generating sites in Switzerland. Different zones will have different effects on the same ES and the program allows this to be user controlled. This way, the burden of cost can be spread among different ES. Klein *et al.* (2009) demonstrated this by altering the desired impact on different commercial fisheries. Individual costs to different ES can also be examined, solving one of the major drawbacks as suggested earlier.

Biotic and abiotic conditions are not static and Marxan with Zones can accommodate this temporal change. Levin *et al.* (2013) show how this can be achieved in terrestrial conservation planning and management of Mediterranean landscapes. It would be possible to adapt this concept to renewable energy concepts when using this software.

The model developed in this study allows for parameters to be changed. It is predicted that future wind turbines will be more efficient in low wind situations and will be more easily transported (Huber *et al.* , 2015). This would create more available wind sites as wind speeds in Switzerland tend to be low. Higher altitude sites that are more difficult to reach would also be open to turbine installation, taking advantage of the stronger winds in these areas. Incorporating these changes would be easily done in Marxan by adjusting parameters and input data.

Huber *et al.* (2015) investigated how conflicts between renewable electricity production and ES provisioning will shape the energy system in Switzerland over the coming years. Marxan can be adapted to run with data representing future patterns of land use in order to evaluate this conflict as it changes over time.

6 Conclusion

Recently, there has been a shift in management priorities from aiming to restore the past, undegraded state of ecosystems, to aiming for 'good environmental status' based on the delivery of ES (O'Higgins & Gilbert, 2014). The incorporation of the ES approach to land use and spatial planning suggests that society can begin to understand, evaluate, and mitigate the effects of our activities on the ecosystems that sustain us (MA, 2003). This signals a move away from making decisions in single sector management, where trade offs are evaluated implicitly, toward using a more holistic EBM approach (Lester *et al.*, 2013). To achieve this, we need to understand the relationship between ecosystem management and the ES values generated and lost under different management scenarios (De Groot *et al.*, 2010). By developing a model to evaluate and weigh different ES against wind electricity production while working towards reaching Switzerland's renewable energy goals, I have successfully integrated the ES approach in a way that allows decision makers to access information in order to make informed policy decisions.

This is the first study to apply Marxan as a tool for developing and visualising scenarios for an onshore wind electricity generating system of turbines. It was used to better understand and manage the conflicts between wind electricity production and ES provided by the landscape. However, it is not the first to find that it is a powerful tool to model how these services and abiotic outputs compete directly for space (Göke & Lamp, 2012). By demonstrating that this optimisation tool can weigh the costs to ES with the benefits of wind electricity production in order to achieve a target output, I have added an instrument to the repertoire of spatial planners. The optimal sites selected by Marxan for wind turbines in the different scenarios give an idea of locations where the highest benefit of electricity production can be gained with the lowest cost to evaluated ES. These give a general idea of which sites should be considered when decision makers are looking to balance this trade off. This is not to suggest that these are the best and only sites, but the results can be used as a guide to focus developing wind farms in certain lower conflict areas. The results, however, depend heavily on the ES assessment used. These values can be easily adjusted by the user.

The present study provides a method that reduces the required number of turbines to achieve a given target amount of electricity than that tested by Segura Morán *et al.* (2014) by 25%. This represents a great potential advantage to planners and decision makers in areas where space is at a premium and renewable energy development faces financial and spatial constraints. In Switzerland, this method should be of great interest as the country moves towards its ambitious energy goals.

The outcomes of these optimisation analyses are suitable for communication with decision makers as they graphically represent suggestions based on a variety of landscape data. This allows scientists to share their findings so that well informed policy decisions can be made. This fulfills the supporting role of science in policy. Policy and decision making is based on the subjective evaluation of information and this study fits well to interpreting important links between society and our environment so that the most desirable outcomes can be found. Future uses of this methodology could better evaluate the potential conflicts between different

types of renewable electricity production and other ES, while offering solutions to mitigate the negative effects of this relationship. This will be integral to Switzerland successfully reaching its ambitious future energy targets in a responsible and socially-accepted way.

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Mt. Crosin wind park, Jura, Switzerland. Photo by the author.

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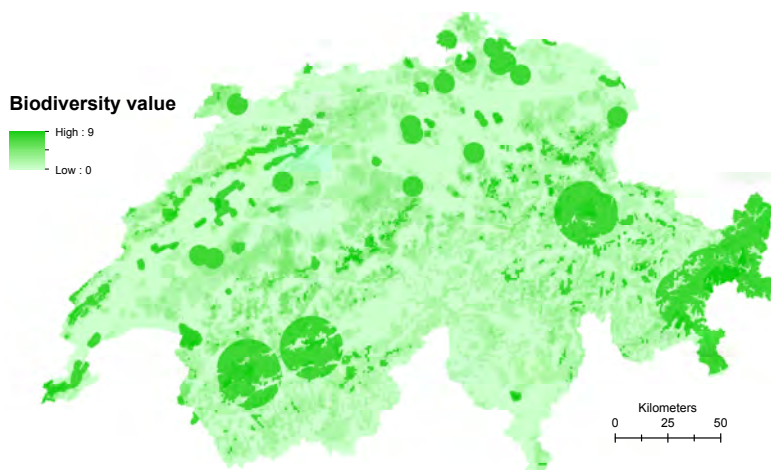
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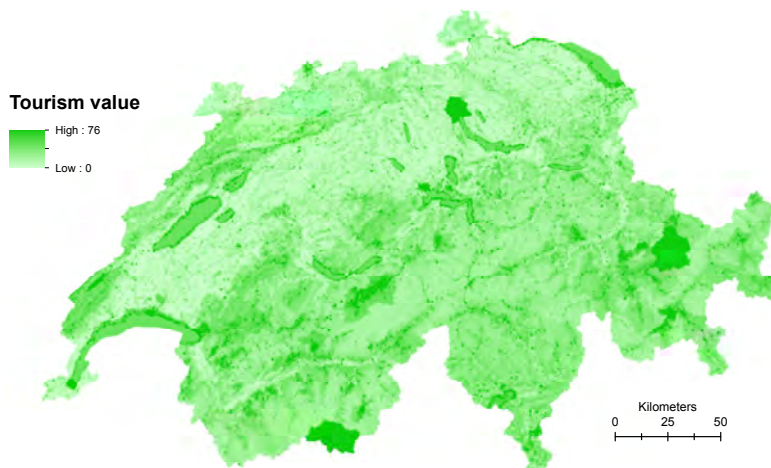
Appendix A Source ES maps



Source data for aesthetics ES.

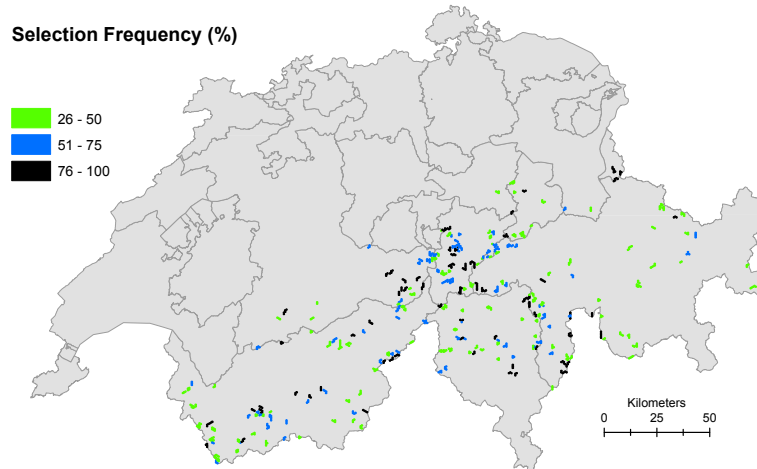


Source data for biodiversity ES.

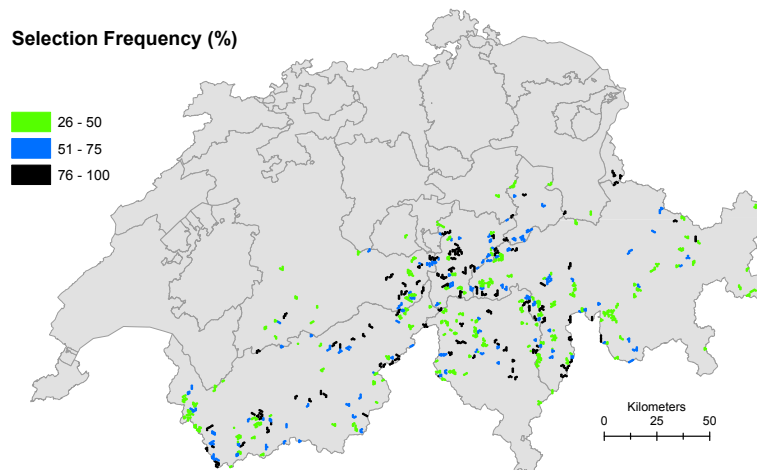


Source data for tourism ES.

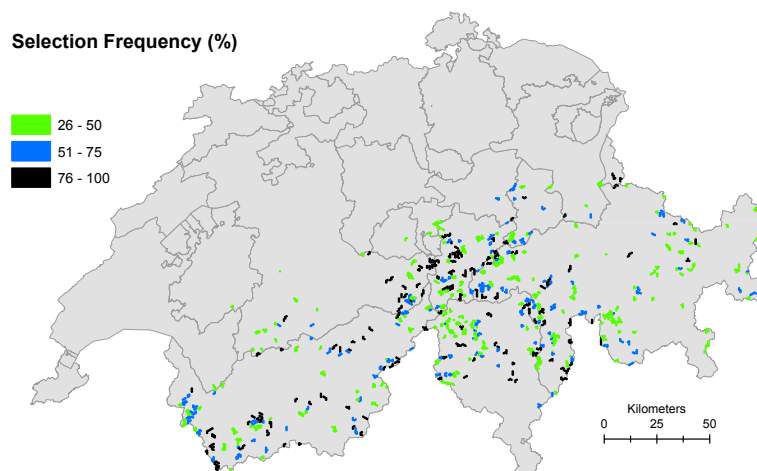
Appendix B Marxan results from scenario B



Selection frequency - 5 TWh target.

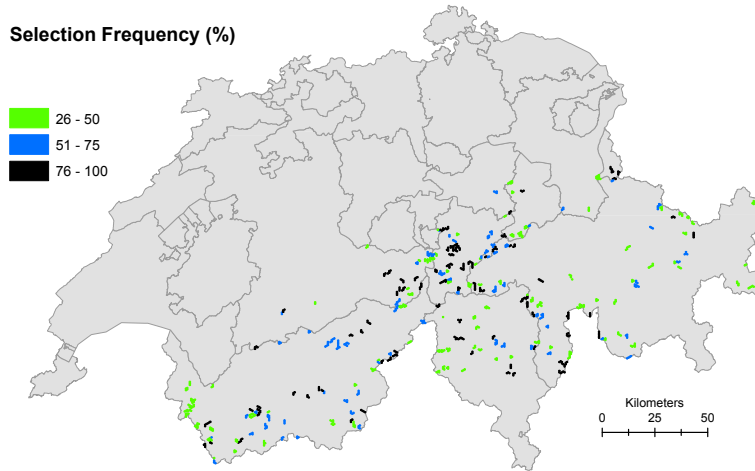


Selection frequency - 8 TWh target.

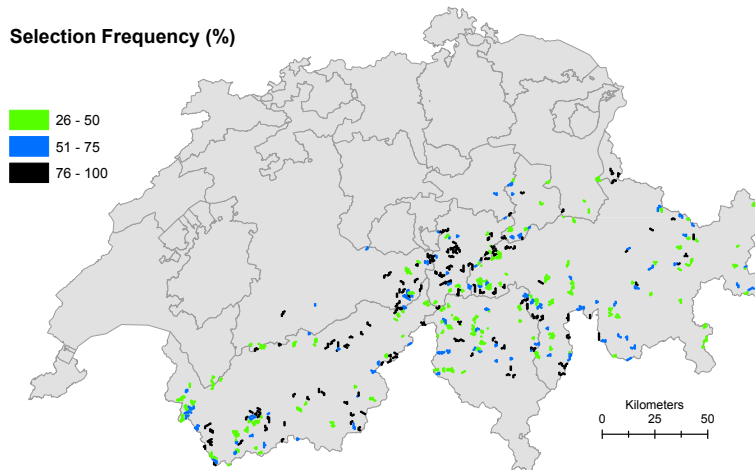


Selection frequency - 10 TWh target.

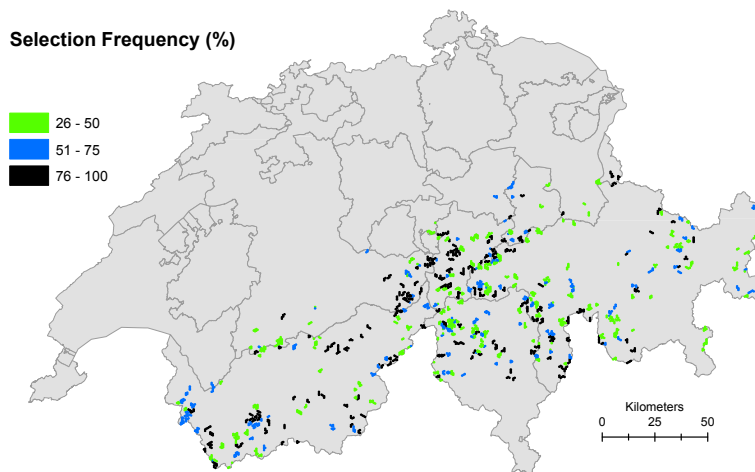
Appendix C Marxan results from scenario C



Selection frequency - 5 TWh target.

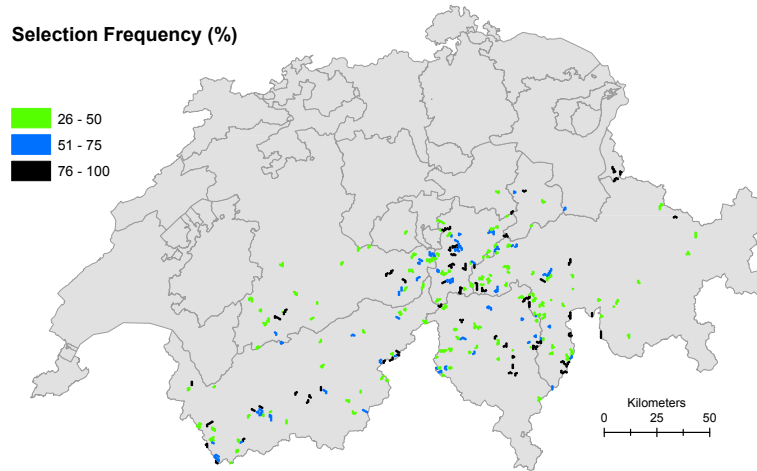


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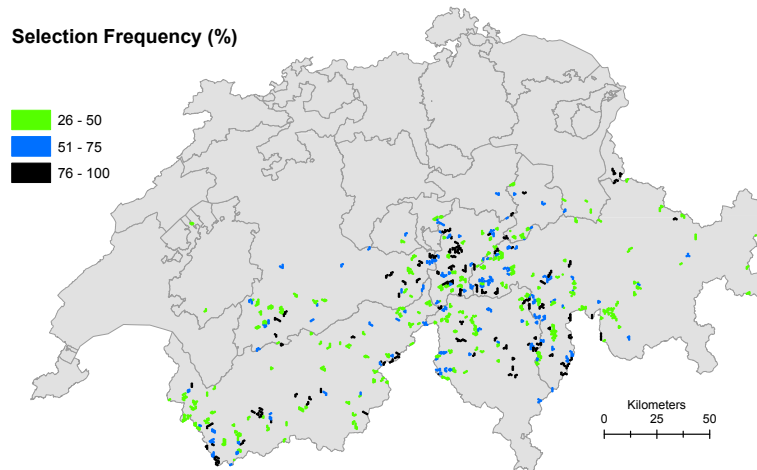


Selection frequency - 10 TWh target.

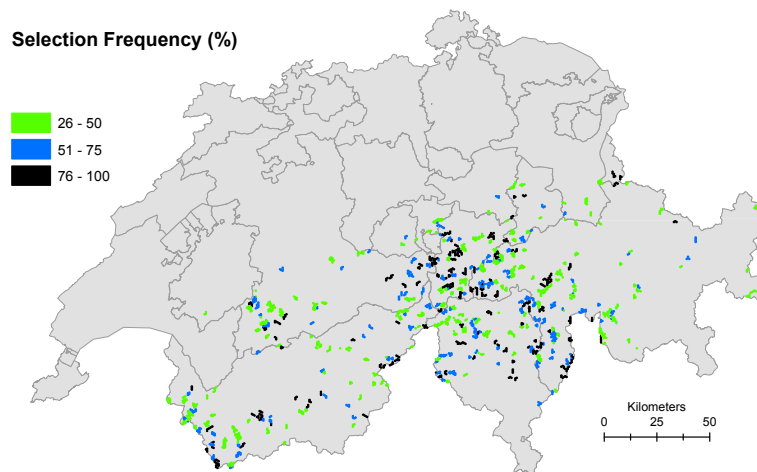
Appendix D Marxan results from scenario D



Selection frequency - 5 TWh target.

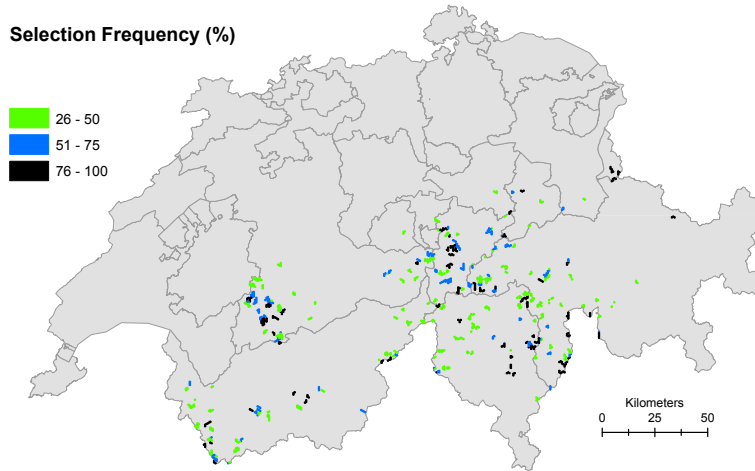


Selection frequency - 8 TWh target.

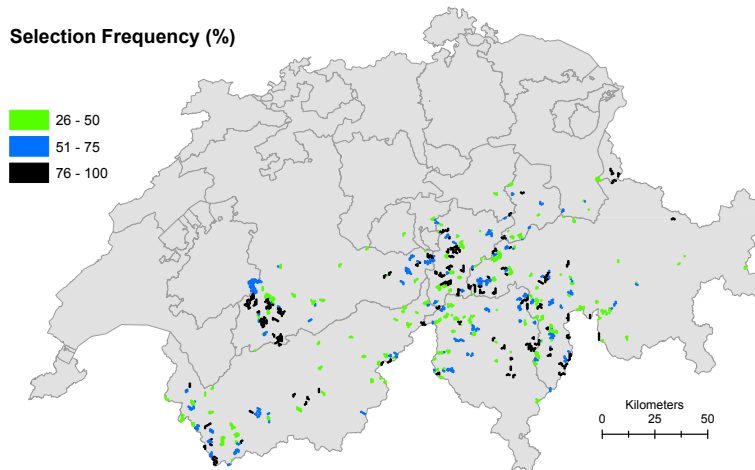


Selection frequency - 10 TWh target.

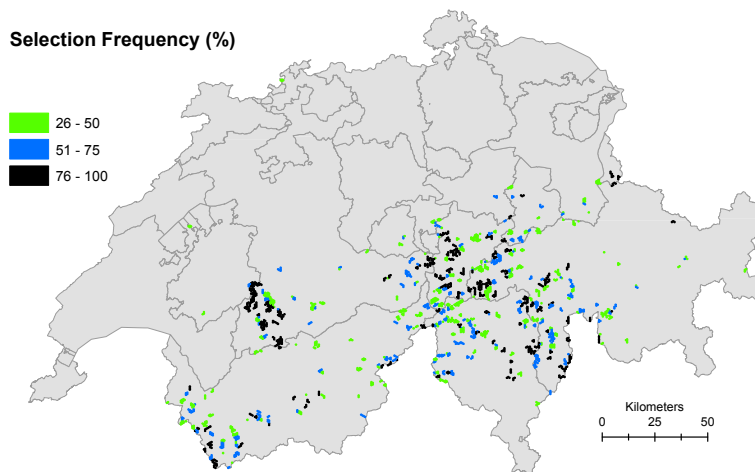
Appendix E Marxan results from scenario E



Selection frequency - 5 TWh target.

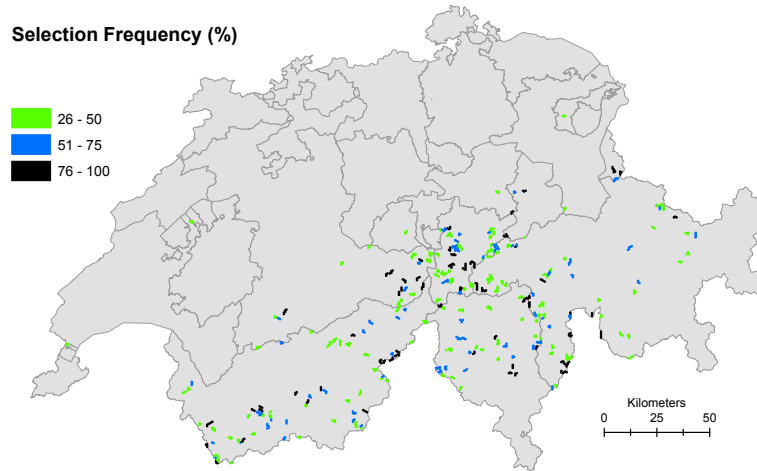


Selection frequency - 8 TWh target.

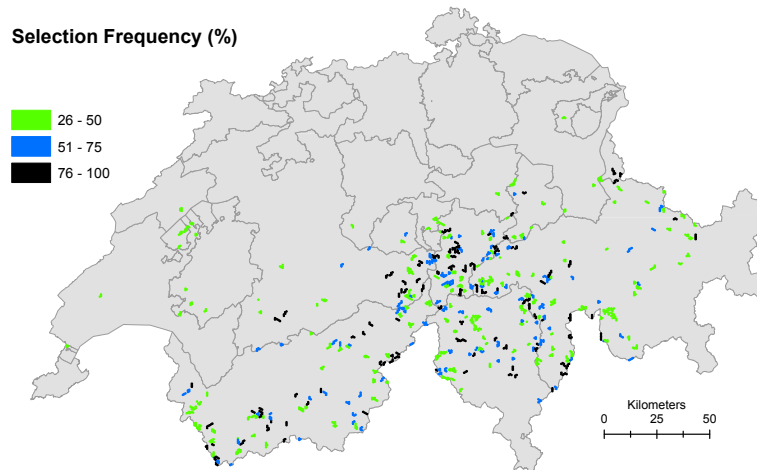


Selection frequency - 10 TWh target.

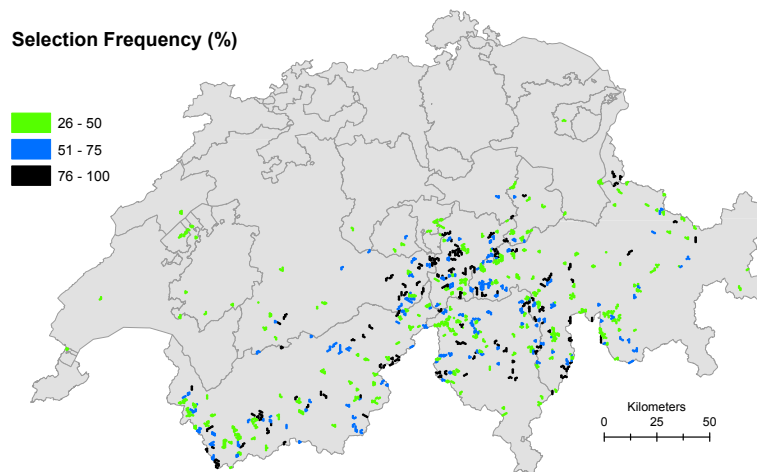
Appendix F Marxan results from scenario F



Selection frequency - 5 TWh target.

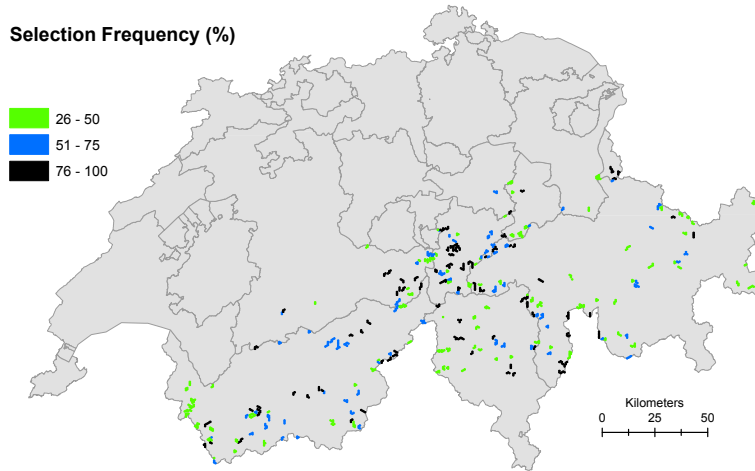


Selection frequency - 8 TWh target.

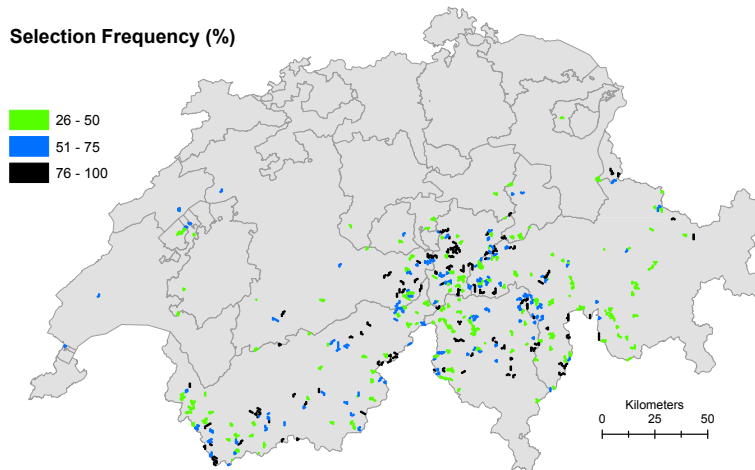


Selection frequency - 10 TWh target.

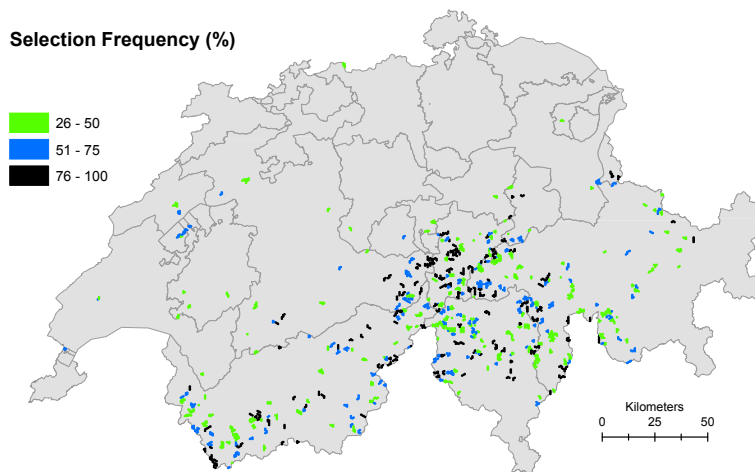
Appendix G Marxan results from scenario G



Selection frequency - 5 TWh target.

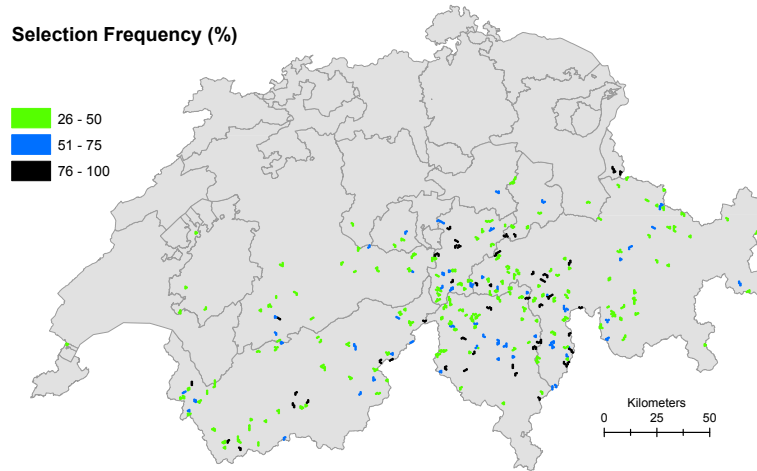


Selection frequency - 8 TWh target.

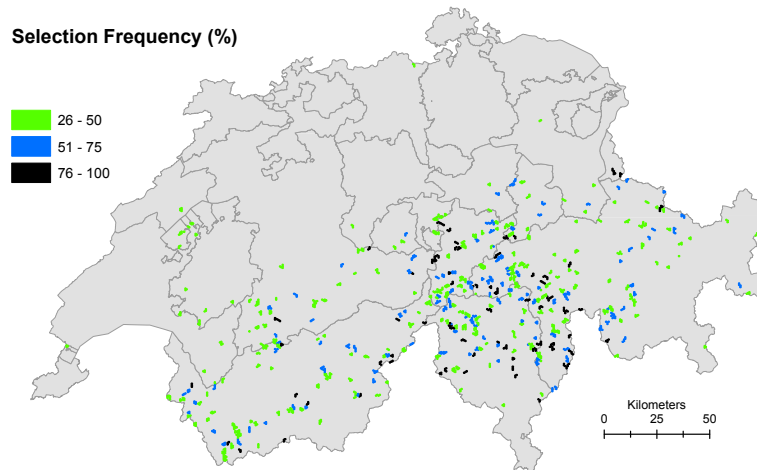


Selection frequency - 10 TWh target.

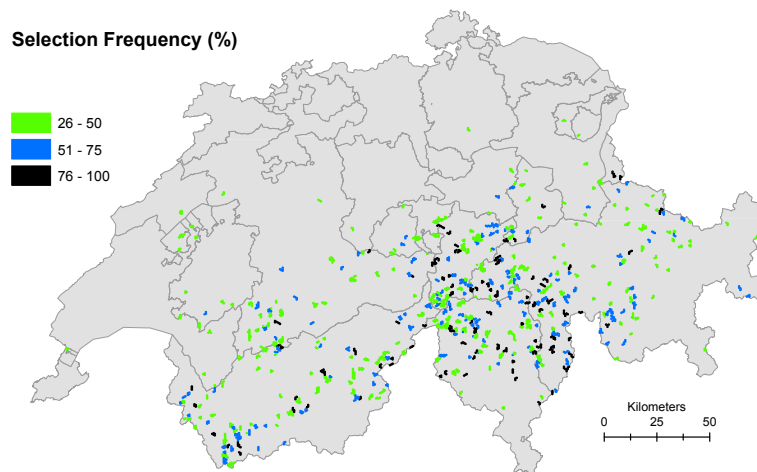
Appendix H Marxan results from scenario H



Selection frequency - 5 TWh target.

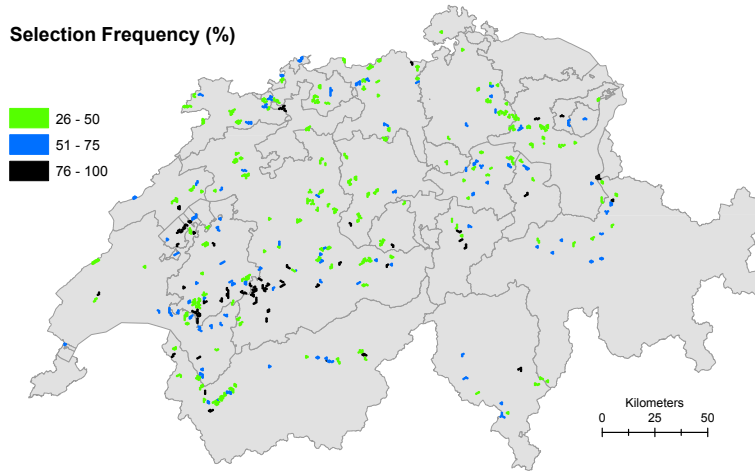


Selection frequency - 8 TWh target.

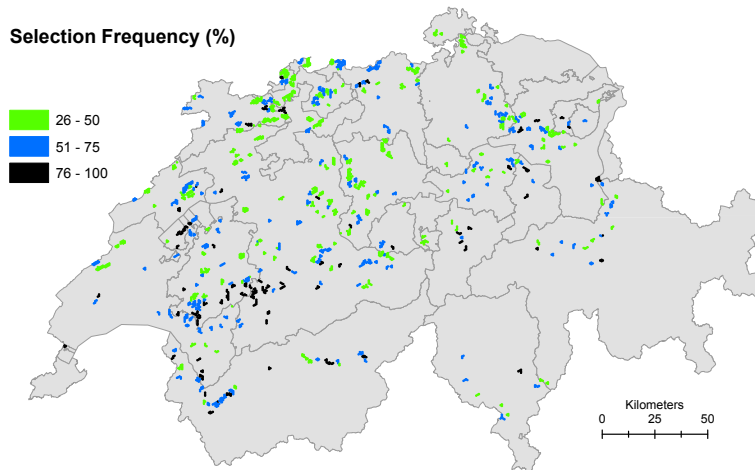


Selection frequency - 10 TWh target.

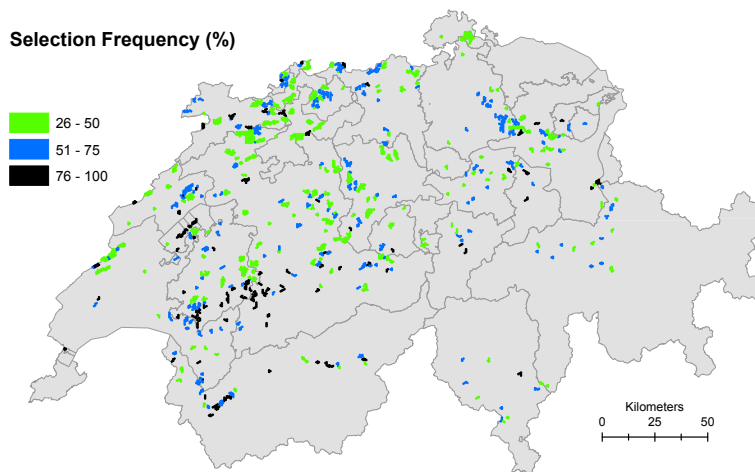
Appendix I Marxan results from scenario I



Selection frequency - 5 TWh target.



Selection frequency - 8 TWh target.



Selection frequency - 10 TWh target.

Declaration of originality

This signed "Declaration of originality" is a required component of any written work (including any electronic version) submitted by a student during the course of studies in Environmental Sciences. For Bachelor and Master theses, a copy of this form is to be attached to the request for diploma.

I hereby declare that this written work is original work which I alone have authored and written in my own words, with the exclusion of proposed corrections.

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