Computing the Past –
Utilizing Historical Data Sources for Map-Based Retrospective Landscape Research

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Summary

Historical topographic maps are unique data sources for retrospective landscape assessments. They can be seen as one of the most reliable representations of the landscape of the past if they date from the time prior to aerial photography. However, the incorporation of such documents in applications such as landscape assessment or land cover change modelling poses numerous and multi-facetted problems. Above all, questions about the reliability of the map information and the extraction of map data from the scanned document have to be answered.

This thesis investigates the applicability of historical topographic maps for land cover change modelling tasks. It focuses on the *forest* cover information in the Siegfried map, the Swiss national topographic map of the 19th century, in order to establish forest cover change models for more than 130 years. The thesis is embedded in the project “Retrospective Assessments” at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) in Birmensdorf, Switzerland. In this project historical map data sources are examined on their applicability for long-term landscape research. The thesis consists of four scientific research papers, which are, in turn, based on three thematically diverse studies.

Paper one is related to the extraction of spatial information from historical topographic maps using methods of pattern recognition. This is attributed to *study one*. An automatic multi-step recognition process based on saliency and semantic processing is developed to extract hand-drawn complex forest cover patterns. This area-based recognition process ensures robustness in extracting the compound forest cover information. It overcomes the complexity and the low graphical quality of the map documents and represents a promising prototype for automatic extraction from larger regions.

Papers two to *four*, which are based on *study two*, are dedicated to the issue of uncertainty. In response to an existing lack in theoretical background on uncertainty within GIScience a conceptual framework for its investigation is proposed. This framework facilitates the exploration of uncertainty in its entire complexity by identifying potential sources and outlining suitable concepts for analysis.

A model for explicit spatial prediction of uncertainty in the historical forest cover representation using Generalized Linear Models (GLM) and moving window techniques is developed in *Paper three*. For this, relationships between mapping quality and environmental variables are used to calibrate the statistical model and to spatially predict uncertainty measures for areas with similar topographic characteristics which are not covered by reference maps.

These predictive uncertainty models are linked to a map correction procedure in *Paper four* based on fuzzy set theory and the modelled uncertainty measures. This procedure improves the biased historical forest/non-forest classification and thus forest cover change analysis which is based on this classification. The method relies on decision rules which consider different identification probabilities during the historical mapping process. The link to predictive uncertainty models allows for the truly predictive improvement of biased survey maps. Thus more reliable forest area estimations can be made for areas of similar topographic characteristics which are not covered by reference maps.

The results of a literature-based investigation in order to examine forest definitions, which existed in the past and influenced the mapping process, are presented in *Study three*. A constructivist approach is suggested for a comprehensive understanding of the meaning and perception of forest in the landscape at that time. Here, forest is understood as a social construction influenced by diverse factors which are considered from a contextualist perspective.

This thesis presents the main findings and methodological approaches developed in the individual papers in response to five central research questions. The contributions of this thesis are brought together in a synopsis by discussing the potential for applying the Siegfried Map to land cover change modelling tasks. The developed approaches increase the reliability of forest cover change models based on the historical spatial information which is captured from the Siegfried Map. The thesis furthers the theoretical understanding and quantitative exploration of uncertainty in GIS-based spatial analysis. Furthermore, it significantly contributes to the field of automatic data capture from scanned topographic maps using pattern recognition methods. Altogether, this thesis presents a comprehensive approach for the systematic examination of historical topographic maps on their applicability to retrospective landscape research. It can be applied to any uncertain historical survey map.

The individual approaches will be further developed and applied to land cover change analysis at larger scales. Alternatively to the presented area-based approach of retrospective exploration, point-based approaches of automated data capture and uncertainty-related change detection will be tested in the near future. These approaches will result in statistical estimations of land cover change.

Zusammenfassung

Historische topographische Karten stellen im Rahmen retrospektiver Landschaftserhebungen einzigartige Datenquellen dar. Sie können als eine der zuverlässigsten Darstellungen der Landschaft in der Vergangenheit betrachtet werden, wenn sie vor Entstehen der ersten Luftbildaufnahmen produziert wurden. Die Nutzung solcher Dokumente für Landschaftserhebungen oder die Modellierung von Landschaftswandel bringt jedoch eine Reihe verschiedenster Probleme mit sich. Zuvorderst stehen dabei Aspekte der Zuverlässigkeit der Karteninformationen und deren Extraktion aus dem gescannten Dokument.

In dieser Arbeit wird die Anwendbarkeit historischer topographischer Karten für die Modellierung von Landschaftsveränderungen untersucht. Am Beispiel der Waldflächen-Daten aus dem Topographischen Atlas der Schweiz (Siegfriedkarte) aus dem 19. Jh. werden Möglichkeiten zur Modellierung von Waldflächenveränderungen über einen Zeitraum von 130 Jahren untersucht. Die Arbeit bildet einen Teil des Projekts „Retrospektive Erhebungen“ an der Eidgenössischen Forschungsanstalt für Wald, Schnee und Landschaft (WSL) in Birmensdorf, Schweiz. Im Rahmen dieses Projekts werden historische Karten auf ihre Verwendbarkeit in der retrospektiven Landschaftsforschung geprüft. Die Dissertation besteht aus vier wissenschaftlichen Forschungsartikeln, welche wiederum auf drei thematisch unterschiedlichen Studien basieren.

Artikel eins befasst sich mit der Extraktion von räumlichen Daten aus historischen topographischen Karten, wobei Methoden der Mustererkennung zur Anwendung kommen. Dies ist Inhalt der *ersten Studie*. Um die von Hand gezeichneten komplexen Waldflächenmuster zu extrahieren, wird ein automatischer stufenweiser Erkennungsprozess entwickelt, der auf den Prinzipien von *Saliency* (Herausragen) und der semantischen Prozessierung basiert. Dieser flächenbasierte Erkennungsprozess ist gekennzeichnet durch eine hohe Robustheit bei der Extraktion der zusammengesetzten Waldflächen-Daten und überwindet somit die geringe Qualität und die Komplexität der Dokumente. Der Prozess stellt somit einen viel versprechenden Prototypen für die Extraktion der Waldfläche in grösserem Umfang dar.

Artikel zwei bis *vier*, welche sich auf die *zweite Studie* abstützen, sind dem Thema Unsicherheit gewidmet. Aufgrund einer unzureichenden theoretischen Grundlage für Unsicherheit innerhalb der Geoinformations-Wissenschaft wird ein konzeptueller Rahmen für die systematische Untersuchung vorgeschlagen. Indem potentielle Unsicherheitsquellen identifiziert und geeignete Analysekonzepte skizziert werden, erleichtert dieser Rahmen die Behandlung von Unsicherheit in ihrer ganzen Komplexität.

In *Artikel drei* wird ein Modell zur räumlich expliziten Vorhersage (Prediktion) von Unsicherheiten in der historischen Walddarstellung entwickelt. Dieses Modell basiert auf Generalisierten linearen Modellen (GLM) und *moving window* Techniken. Beziehungen zwischen der Kartierungsqualität und Umgebungsvariablen werden hierbei genutzt, um ein statistisches Modell zu kalibrieren. Dieses Modell ermöglicht die räumliche Vorhersage von Unsicherheiten in Gebieten mit ähnlichen topographischen Eigenschaften, für welche keine Referenz-Karten existieren.

An dieses Modell knüpft in *Artikel vier* eine Korrekturprozedur für Karten an. Basierend auf der Unscharfen Mengentheorie (*fuzzy set theory*) und den modellierten Unsicherheiten wird die verzerrte (*biased*) Wald/Nichtwald Klassifizierung in der Karte als auch die auf diese Karte bezogene Veränderungsanalyse verbessert. Dafür werden Entscheidungsregeln formuliert, die sich auf die Annahme von unterschiedlichen Identifizierungswahrscheinlichkeiten während der historischen Kartierung stützen. Die direkte Verbindung zu den Unsicherheitsmodellen erlaubt die prediktive Anwendung der Korrekturanalyse in topographisch ähnlichen Regionen, für die keine Referenzkarten zur Verfügung stehen.

Die Resultate einer Literaturrecherche zur Erörterung von historischen Walddefinitionen und Einflüssen auf den Kartierungsprozess werden in der *dritten Studie* vorgestellt. Ein konstruktivistischer Zugang wird vorgeschlagen, welcher ein umfassendes Verständnis über die Bedeutung und Wahrnehmung des Waldes in der damaligen Landschaft ermöglicht. Dabei wird Wald als soziales Konstrukt verstanden, welches von unterschiedlichen Faktoren beeinflusst wird. Diese Faktoren werden aus einer kontextualistischen Perspektive beleuchtet.

Die zentralen Resultate und methodischen Ansätze, welche in den vier Artikeln präsentiert werden dienen der Beantwortung von fünf Leitfragen. Die einzelnen Beiträge dieser Arbeit werden in einer Synthese zusammengebracht, indem insbesondere das Potential der Siegfried-Karte für die Modellierung von Landschaftswandel diskutiert wird. Die präsentierten Ansätze erhöhen die Zuverlässigkeit von räumlichen Analysen zur Waldflächenflächenveränderung, die auf den historischen Karteninformationen basieren. Die Dissertation erweitert zudem das theoretische Verständnis von Unsicherheit und stellt neue Ansätze zur quantitativen Analyse von Unsicherheit in GIS-basierten räumlichen Analysen vor. Zudem leistet sie einen signifikanten Beitrag zum Forschungsfeld der automatischen Informations-Extraktion aus gescannten topographischen Karten. Insgesamt wird in dieser Arbeit ein umfassender Ansatz zur systematischen Untersuchung von historischen topographischen Karten präsentiert, welcher für historische Karten im Allgemeinen Gültigkeit findet.

Die einzelnen Ansätze, die in dieser Arbeit vorgestellt wurden, sollen im Rahmen von Landschaftsveränderungsanalysen in grösserem Massstab weiter entwickelt und getestet werden. Zusätzlich zu den hier vorgestellten flächen-basierten Ansätzen werden in naher Zukunft *punkt-basierte* Ansätze zur automatischen Datenerfassung und *unsicherheits-basierten* Analyse getestet, um statistische Masse zum Landschaftswandel herzuleiten.

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Stefan Leyk

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Part I

Synopsis

Chapter 1

Introduction

The research presented in this thesis is part of the project "Retrospective Assessments", being undertaken at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) in Birmensdorf, which encompasses the investigation of historical map data sources in regard to their use in landscape research. Thus, unique historical data sources are intended to be evaluated for their potential to be applied in land use and land cover change models.

1.1 Background

Research on changes and dynamics in the landscape have been well established during the past decades. Key topics are land cover change, land use change or landscape reconstruction from different points of view, such as ecology (Bolliger *et al*. 2004), forestry (Manies *et al.* 2001), landscape management (Cissel *et al*. 1999) or population dynamics. The knowledge of past states of the landscape and the comparison to data from different times helps to better understand the landscape dynamics and to better manage our environment in a sustainable manner (Swetnam *et al*. 1999). Various studies are based on remotely sensed data such as aerial photos (Mast *et al*. 1997, Alard 2001) or satellite imagery (Sachs *et al*. 1998). Other scholars are using historical inventory or survey data (Comer *et al*. 1995, Axelsson 2001, Mladenoff *et al*. 2002, Bolliger *et al*. 2004) or map data. Depending on the scale and thematic focus of the research either cadastral maps (Skanes 1996, Domaas *et al*. 2001) or topographic maps (Hodgson and Alexander 1990, Kienast 1993) were shown to be suitable historical data sources.

Historical topographic maps are available for times going back more than 200 years. They show acceptable accuracy from the 19th century onwards. Thus, they contain a complexity of information about the landscape in a two- or three-dimensional spatial representation. This is a significant advantage compared to survey data which only allow for statistical or qualitative evaluations and do not provide spatial information *per se*. Aerial photography was not established before the 1920s and its applicability is thus limited to more recent times. A map is a scale-bound structural model of spatial relationships characterised by a system of geometrically predefined graphical entities (Hake *et al*. 2002). In this sense, a topographic map is a simplified spatial representation of the landscape and the relationships between individual landscape elements. These are bound to predefined rules for representation. Thus numerous topographic maps produced during the last two centuries have a great potential to be used for land cover change investigations. The Siegfried Map, the Swiss national topographic map in the 19th century (Figure 1), carries such potential. It is the object of investigation in the presented dissertation. More precisely, the focus lies on the forest cover represented in the Siegfried Map to answer the question whether the map can be used in applications of forest cover change modelling.

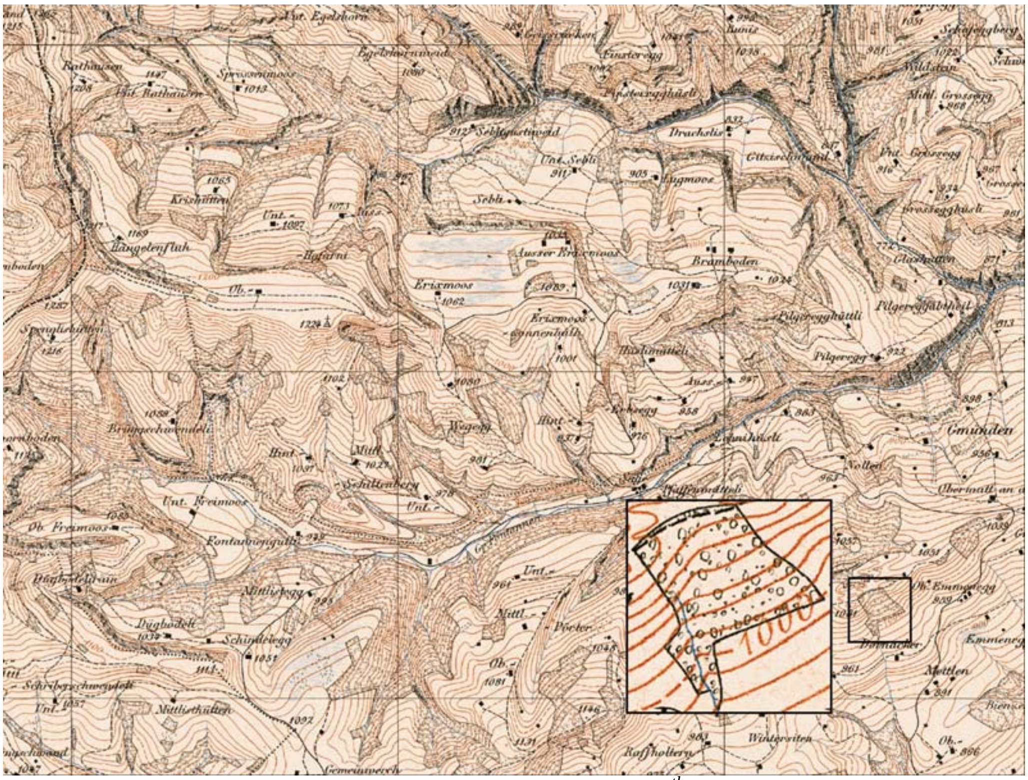

Figure 1. The Swiss national topographic map in the 19th century, the Siegfried Map. The zoomed box shows the graphical representation of forest cover.

1.2 Motivation

To date only vague estimates exist about the forest area and its distribution in Switzerland in the 19th century. Survey-based estimations are not reliable due to inconsistencies and a lack of information concerning the survey methods applied (Decoppet 1913, Brändli 2000). Consequently, estimates of changes in forest area and its distribution suffer from this unreliability, too. Thus the original motivation for this thesis was the need of more accurate and reliable estimations of the historical distribution of forest cover at the end of the 19th century in Switzerland. Such information could be used as a basis of historical data for the analysis of forest cover change. The forest cover in the Siegfried Map is the only spatially oriented representation of forests in the 19th century which covers all of Switzerland. Thus it represents a unique and valuable data source for comparison with information on the present state. For example, comparison with forest survey data, such as the Swiss National Forest Inventory (NFI), would allow for a point-based approach of forest cover change analysis by designing a historical inventory on the Siegfried Map and simulating a forest/ non-forest decision (Figure 2). On the other hand, the comparison with forest cover from current topographic maps would enable an area-based approach in which the entire cover is included for spatially explicit analysis (Figure 2). In this thesis the area-based approach is aimed at considering a spatially oriented procedure. Geographical Information Systems (GIS) allow for efficient management and analysis of geographical data in a spatial context and thus for the computation of such changes and dynamics based on multi-temporal GIS operations (Vrana 1989).

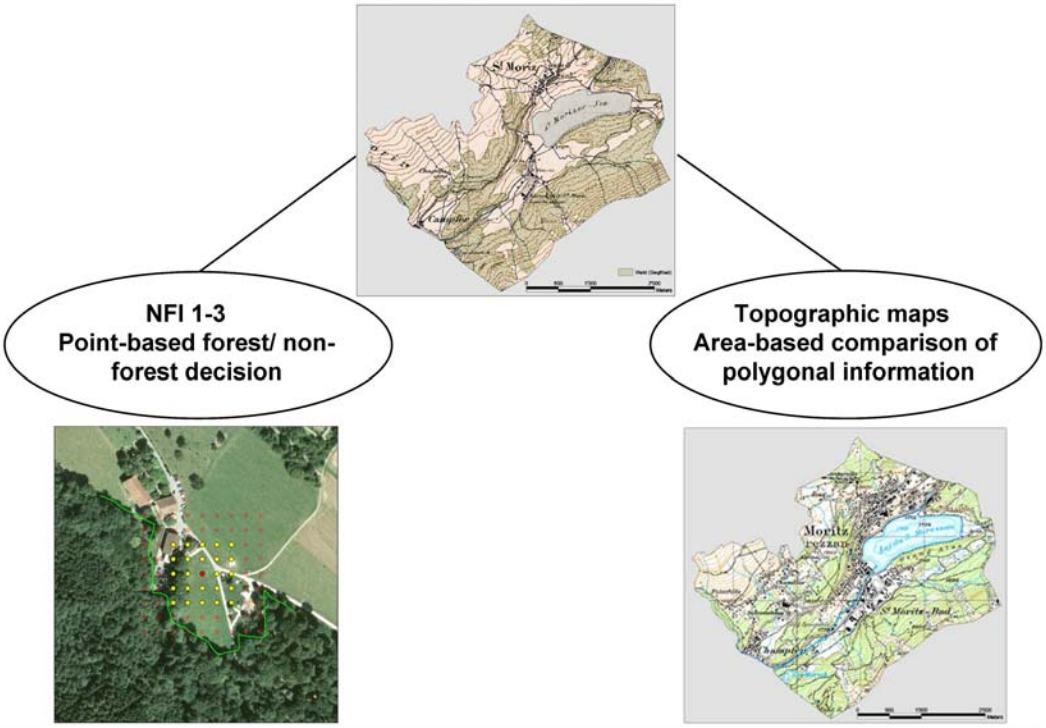

Figure 2. Land cover change analysis based on evaluated historical map data can be conducted as a point-based or an area-based approach to derive statistical or spatially oriented results, respectively.

1.3 Challenges

Before a GIS-based change analysis can be conducted several challenges have to be identified. The historical paper maps were scanned in a preliminary phase. To incorporate the information of interest into GIS-based spatial analyses it has to be extracted or recognized as completely as possible from the raw scanned maps. This is one challenge. Considering the fact that more than 6000 map sheets exist, an automated approach for this extraction is needed. For this purpose sophisticated methods of digital image analysis are needed. This is a particularly challenging task due to the complexity of the map information and the low quality of the document. Forest cover in the Siegfried Map is not simply represented by a contiguous colour layer as in modern topographic maps but by complex patterns defined by the spatial arrangement of single symbols and boundaries (Figure 3). To extract this complex information completely for an area-based approach of forest cover change analysis, advanced methods of pattern recognition have to be applied.

The second challenge is related to the quality of the historical spatial data. The uncertainty inherent in a historical map from the 19th century and its incorporation in spatial analyses needs to be considered. Before any operation in a GIS can be done, the uncertainties of the data themselves, as well as those which relate to the intended operations, have to be investigated. This means the different types of uncertainty have to be identified, conceptually understood and, if possible, quantitatively assessed. Finally, ways of using this knowledge of uncertainty for the improvement of the planned target application are needed. This thesis investigates such ways of conceptual and analytical treatment of uncertainty.

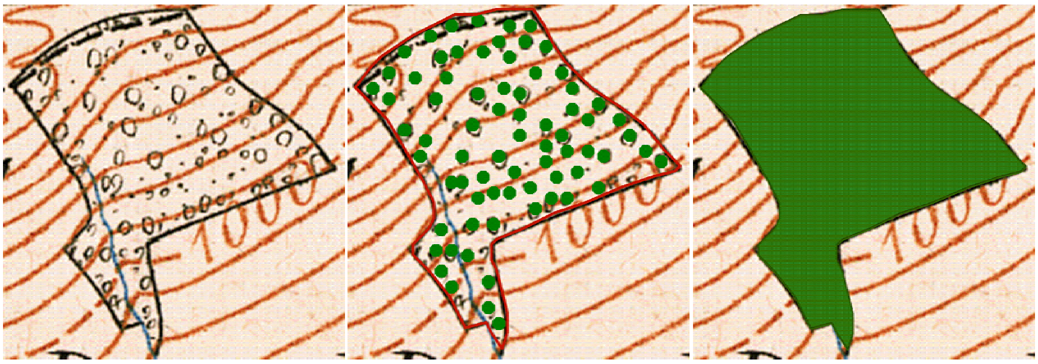

Figure 3. Symbolic illustration of forest cover extraction. Individual forest symbols and forest boundaries have to be recognised to completely define the spatial extent of the forest patch.

1.4 Research questions

According to the challenges described above, five research questions are dealt with in this thesis. The first question considers the problem of information extraction. Questions II to V are related to the problems of uncertainty investigation, uncertainty modelling and uncertainty based land cover change analysis. In detail these questions can be formulated as follows.

(I) *Can we develop methods of automatic and robust extraction of the forest cover information from the scanned maps to carry out an area-based approach to analysis?*

(II) *What is the suitable theoretical concept for the investigation of uncertainty in using the data for land cover change modelling and for understanding the individual components of uncertainty?*

(III) *Are there ways to quantitatively assess inherent uncertainty at any location in a historical map and to predict its variability in space for areas which are not covered by reference data?*

(IV) *How can uncertainty information be effectively used for the improvement of map-based land cover change applications?*

(V) *Which historical definition can be assumed for forest cover representations in the Siegfried Map and can its semantic meaning be derived?*

These five questions are the focal points examined in this thesis. Thus they were used to formulate aims and scopes and to define the basic structure of the research. They are dealt with in different studies as described below. Figure 4 presents a graphical overview of the individual parts making up the thesis in response to the research questions and links between them.

1.5 Aims and scopes

Each of the research questions described above is related to a distinct and sharply defined aim, yet ensuring a certain complementary character to all other questions. They are important key questions within the project “Retrospective Assessments”, regarding the evaluation of the historical data source for its applicability to landscape research. The intention of this thesis is to present these foci as single research components and at the same time to outline links between them. In this context, the overarching aim of the thesis is the evaluation of historical map-based information for its applicability to retrospective landscape assessments and land cover change analyses. To achieve this goal, different aspects have to be considered which have already been mentioned in the challenges section. Below, the individual aims which are related to the research questions are briefly outlined.

The question of whether the historical map can be used for the intended area-based landscape research first touches the fields of digital information extraction, pattern recognition and document analysis. The aim, related to *research question (I)* (Figure 4), is thus the automated extraction of forest cover information from the manually produced scanned historical map to eventually incorporate as a vectorised forest polygon layer in GIS. This step can be understood as the translation from unreadable digital spatial information to a GIS-readable format via cartographic pattern recognition.

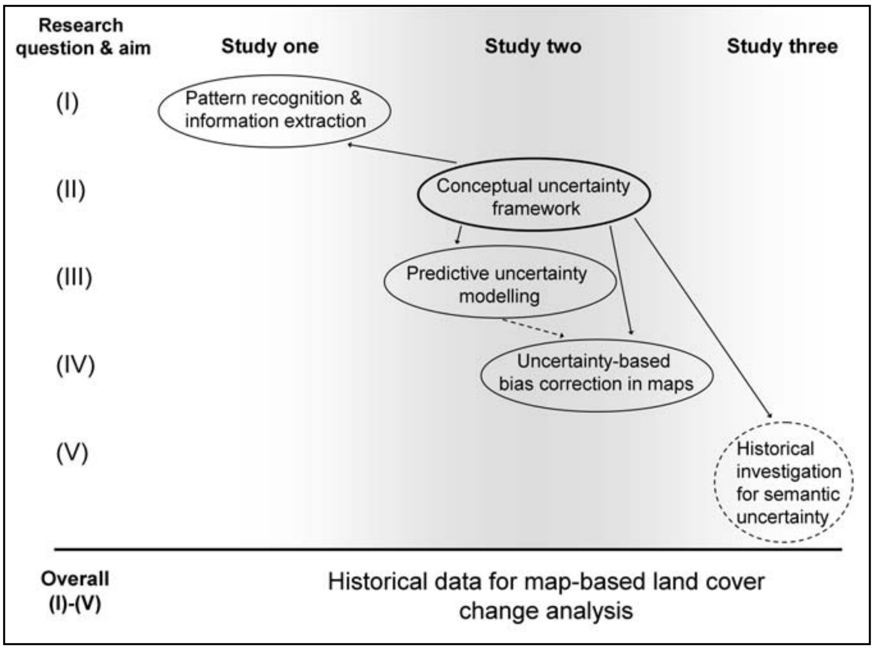

Figure 4. Overview of individual parts of the thesis. Study one is related to the extraction of forest information in response to research question I. Study two encompasses conceptual and analytical aspects of uncertainty and focuses on research questions II to IV. Study three is dedicated to the historical investigation of forest terms and definitions used in the 19th century.

The existence of uncertainty in spatial information has received increasing attention within the GIS research community during the last two decades. Nevertheless, there are many questions left to be answered considering the conceptual nature and understanding of uncertainty and its analytical treatment in the context of spatial data. Since maps from the 19th century evidently come along with considerable amounts of uncertainty, the topic has to be given highest priority from the perspective of landscape research. To reduce confusion in the scientific terminology of uncertainty-related aspects, the aim in correspondence with *research question (II)* (Figure 4) is to establish a suitable framework for uncertainty investigation. Such a framework for using map-based information in land cover change applications is missing to date.

Here, the intention is to further the understanding of the nature of uncertainty, to identify potential sources and to evaluate the impact on the target applications. Thus, the aim is to facilitate the systematic analytical treatment of uncertainty for a scientific approach.

Since reference data for historical spatial information from the 19th century are scarce, the quantitative analysis of inherent uncertainty within reference areas, which has frequently been done, needs to be extended. According to *research question (III)* (Figure 4), an uncertainty model will be established to spatially characterize the quality of the historical forest cover mapping. The aim is to establish statistical models and explanatory rules and to derive spatially explicit predictions of inherent uncertainty for areas which are not covered by reference data. Such models have not been established yet and are therefore of a highly innovative character.

To answer *research question (IV)* such predictive uncertainty models will be examined for incorporation in land cover change analyses (Figure 4). The aim is to use the quantitative uncertainty information for effective improvement of the historical map and area estimations derived from it. This would also allow for more reliable land cover change analyses.

Finally, a methodological outline and preliminary results from a historical investigation are presented in response to *research question (V)*. The outline describes the fundamental approach for deriving a historical forest definition used during the historical field survey.

1.6 Three studies, four papers

Three studies were conducted to answer the five research questions and to reach the aims formulated above (Figure 4). *Study one* deals with *research question (I)* and is thus dedicated to aspects of automated data capture from scanned topographic documents by pattern recognition procedures. This implies sophisticated approaches in the fields of digital image analysis, cartographic pattern recognition and information extraction. *Study two* encompasses *research questions (II)* to *(IV)* considering the analytical evaluation of uncertain historical map information and conceptual issues of uncertainty. It touches the field of GIS-based uncertainty modelling by probabilistic and possibilistic approaches. *Study three* is related to *research question (V)* and thus to the historical investigation of the map to derive forest definitions potentially used in the Siegfried Map. Table 1 shows the relationships between studies, papers and research questions in completion to Figure 4.

Research questions (I) to (IV) are each dealt with in a separate research paper according to the aims formulated (Figure 4, Table 1). *Study three* is not subject to a paper but its preliminary results are briefly described in Section two. Short summaries of each of the four research papers are given in Chapter four. The complete versions of these papers are attached in part II at the end of this thesis.

Study	Research question	Paper	Key words
One	I	***One***	Pattern recognition and information extraction
Two	II	***Two***	Uncertainty concepts
	III	***Three***	Uncertainty analysis and predictive modelling
	IV	***Four***	Uncertainty-based map correction using fuzzy sets
Three	V	-	Historical investigation and forest definitions

Table 1. Overview and relationships between studies, research questions and papers.

1.7 Structure of the thesis

This thesis is based on four research papers published or submitted to international scientific journals. These papers each focus on a specific topic in response to one of the research questions described in the previous section. The research papers are:

Paper one:

Leyk S, Boesch R, and Weibel R (in press) Saliency and semantic processing: Extracting forest cover from historical topographic maps. *Pattern Recognition*

Paper two:

Leyk S, Boesch R, and Weibel R 2005 A conceptual framework for uncertainty investigation in map-based land cover change modeling. *Transactions in GIS* 9(3): 291-322

Paper three:

Leyk S, Zimmermann N E 2004 A predictive uncertainty model for field-based survey maps using generalized linear models . In: Egenhofer M J, Freksa C, and Miller H J (Eds.) Geographic Information Science, GIScience 2004. *Lecture Notes in Computer Science* 3234: 191-205. Springer Verlag

Paper four:

Leyk S, Zimmermann N E (submitted) Improving land change detection based on uncertain survey maps using fuzzy sets. Submitted to *Landscape Ecology*

This volume consists of two parts. ***Part one*** (synopsis) is organised in six chapters. The *introductory* sections in **Chapter one** provide information about the *background* and the original *motivation* of the research presented. Specific *challenges*, *research questions* and *aims* and *scopes* of the thesis are described in the following sections. The introduction ends with a short presentation of the three studies upon which the conducted research is based. In **Chapter two**, which describes a separate study, the historical investigation to derive important information about political, institutional and, societal issues in Switzerland of the 19th century is described. **Chapter three** reviews current trends in the scientific fields touched on by this thesis. Here key methods are highlighted and positioned within the current research areas, providing the background which cannot be given within the scientific papers. Short summaries of the four research papers, listed above, are given in **Chapter four**. Finally, **Chapter five** is dedicated to the discussion. **Chapter six** provides a comprehensive conclusion regarding the links between the individual parts of the thesis to highlight its synoptical character. ***Part two*** presents the four research papers as they appeared in or were submitted to the sources given above.

Chapter 2

The Siegfried Map: A historical investigation into the semantics of forest definitions in the 19th century

The Siegfried Map (officially called the *Topographical Atlas of Switzerland*) represents a unique data source from the perspective of landscape research but also with regard to other scientific fields such as social sciences, history and, urban sciences. The map is not only a spatial witness of the past landscape but also a result of interesting historical events and important societal and political developments. Unfortunately, forest definitions did not exist *per se* in the 19th century and instructions were formulated without explicit consideration of forests. This lack in semantic information leads to considerable amounts of inherent or production-oriented uncertainty. This becomes apparent when the forest cover from the Siegfried Map is compared to newer data sources where forest is defined differently (*Paper two*). For this reason a historical investigation has been conducted to derive semantic knowledge of the map contents, in particular forest cover.

Due to the lack of objective reference data, an approach is suggested to reconstruct the perception of forests in the 19th century. Influenced by different factors such as forestry, politics, society and economy the topographer identifies forest in the field based on his individual perception. The final aim is the derivation of a historical forest image or concept of what could have been mapped if forest cover is found in the Siegfried Map based on a *constructivist* approach. This term is formulated more precisely then, based on available reference data which are scarce for the time in question. This part represents a separate study of the thesis (*study three*, Figure 4). Here only the results of the historical investigation and an outlook of the approach borrowing methods from the social sciences are described. The continuation of the study will be resumed in the near future.

Below, the Siegfried Map, its initiation, the used survey methods as well as available reference data are described. Historical aspects embracing politics, cartography, forestry, society and other fields which influenced the initiation of the field campaign under the leadership of Hermann Siegfried are systematically elucidated. This is to develop an understanding of the historical circumstances and attitudes towards natural objects in the 19^{th} century. The outline of the interpretational approach is presented at the end of this chapter.

2.1 The initiation of the Siegfried field campaign

In this thesis the first edition of the Siegfried Map or “Siegfried-Atlas” which was published between 1868 and 1901 is considered. The publication of the Dufour Map (1832-1864), the preceding Swiss national topographic map at the scale of 1:100,000, and other regional or Cantonal maps (Michaelis, Wild or Eschmann) brought Swiss cartography into a leading position in Europe (Gugerli and Speich 2002). This resulted in the strengthening of the position of the Federal Topographical Bureau in Berne within the young Swiss federal state. The increasing needs of the public, the tourism sector, science and the military for more accurate maps and the growing trade, railroad and road construction led to the urgent demand for a new topographic map (Antiker 1927).

In the year 1863, Herrmann Siegfried, the director of the Federal Topographic Bureau, proposed the production of a new National topographic map based on the Dufour Map in collaboration with the Swiss Alpine Club (SAC). In 1868, two federal laws were enacted to place the matter in the hands of the Topographic Bureau and instructions and regulations were formulated (Schneider 1938, Oberli 1968). The original field books from the Dufour Map field campaign were used as the basis for the new map (Grob 1941). The aim was to publish this new map at the scale of the original field books, and thus at the scale 1:25,000 for the Central Plateau, Ticino, Pre-Alps and Jura and the scale of 1:50,000 for the Alpine region. The regulations of the two new laws contained guidelines considering the surveys, revisions and updates of the map sheets and the assurance of the triangulation points. The triangulation network, consisting of points of the first, second and third order, remained the same as for the Dufour field campaign. Thus the first edition of the Siegfried Map was based on the old Berne coordinate system (Imhof 1927, Schneider 1938). In 1878, a federal ordinance was enacted to establish triangulation points of the fourth order within the area of the federal forests (Ganz 1938) as preceding step to cadastral mapping.

The main problem was that during the Dufour campaign assessments in the field were done with the knowledge that the final map would be published scales two or four times smaller. The revisions within this new project were aimed at the production of maps at the same scale. In 1901, almost all map sheets (464 at the scale of 1:25,000 and 132 at 1:50,000) were published. During this time a confusing process of revisions in single map sheets started influenced by continuously renewed and modified instructions and regulations and a new triangulation base after 1890 (Grob 1941). The result is a conglomerate of frequently updated map sheets which lacks homogeneity. Nevertheless, the map satisfied the requirements for scientific and military purposes until the 1920s.

2.2 Methods and techniques used for field survey and reproduction

For measuring in the field, graphical triangulation on ordnance survey maps was applied as one of the traditional techniques. The equipment consisted of a measuring table, a “Kippregel” with vertical circle (Figure 5), rotatable field glasses with crosshairs and, a transversal ruler and dividers. For determining the right position, the triangulation points were immediately drawn onto the field map to obtain the required scale and orientation (Grosjean 1996). The distances to these points were determined by the "stroke distance method" ("*Strichdistanzmessung*"). The elevation difference between the position and the triangulation point was calculated based on the angle between them. With this method the map was immediately produced and corrections could be made in the field. One disadvantage was the fixed scale used. Based on the measured triangulation points the details of the map, such as buildings or forest boundaries, were drawn into the field books by the topographer. Thus subjectivity in the registration of objects could not be prevented. It is obvious that the accuracy of the measuring was dependent on the number of triangulation points, the technique used, and the capability of the topographer.

The reproduction of the map sheets was done manually. Maps at the scale of 1:25,000 were produced by copper plate engraving at the manufacturer Müllhaupt. The lithographer Leuzinger was charged with the reproduction of map sheets at the scale of 1:50,000 by stone engraving (Oberli 1968). This bipartition had consequences for the updating and revision process of the map sheets over the following years. Copper plates allow an easier correction than lithographs. This fact has to be considered for change detection based on different editions of the Siegfried Map. Detailed information about the reproduction of map sheets is hardly available today. Graphics show a high degree of variability due to the manual production. Only text follows some rules in size and shape, which leads to the conclusion that stencils were used.

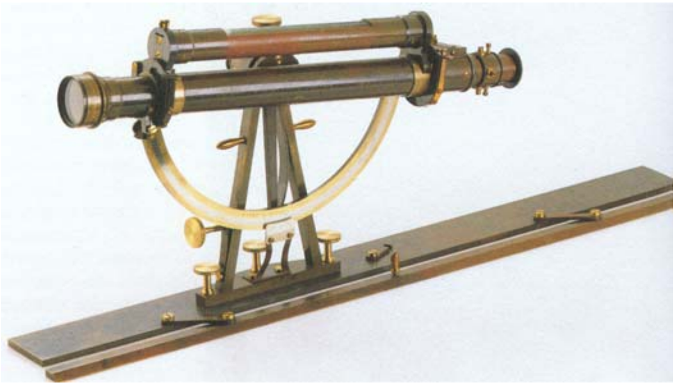

Figure 5. "Kippregel" with vertical circle and rotatable field glasses used during the field survey of the Siegfried Map (source: Ammann and Meier 1999).

2.2 Graphical representation in the Siegfried Map

Several new features were incorporated in the representation of the Siegfried Map compared to the Dufour Map. The most important change is the use of elevation contours instead of hachure. From the present-day perspective this is one prerequisite for the automated interpretation of the digital map data and the extraction of the map contents. The elevation contours are represented by red lines (Figure 6). They were drawn at an equidistance of 10 m on map sheets of the scale 1:25,000 and 30 m on maps of the scale 1:50,000 (Siegfried 1871, Lochmann 1888a, b, c). These are the same rules which were already applied during the Dufour field survey (Dufour 1834a, b, Feldmann 1999). The small equidistance of 10m had the consequence that elevation contours on steep slopes come too close together and cover a great portion of the map content (Antiker 1927).

The map content, in turn, consisted of different land cover classes resulting in a high density of information. Background was left colourless and thus it carries the beige colour of the original paper used for printing. Lakes, rivers, and wetlands are represented in blue. All other landscape elements belong to the black layer. These are forest, road network and rail roads, buildings, rock, and vineyards. Throughout the entire map an abundance of place names and numbers occur.

Forest cover as object of interest in this thesis is represented as small black circle-like symbols and dots irregularly distributed over space (Figure 6). The forest boundary was drawn as a thin black line for “closed forests”. In cases of “open stands” or “forest and pasture” no boundary appeared (Siegfried 1871a, b, c). Thus only these two forest categories were differentiated during the field survey. Basically, forest was of minor importance during the mapping. The survey instructions did not explain any detail or definition of how the topographer had to identify forest in the field. Thus forest assignment in the map was, to a high degree, a matter of subjective decision by the topographer in particular where forest was drawn as open forest.

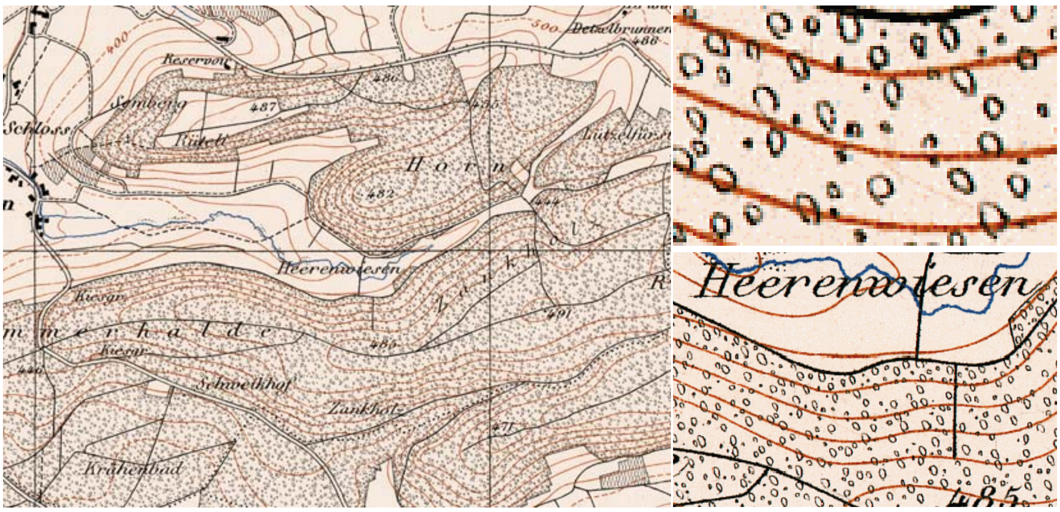

Figure 6. Example of the graphical representation of forest in the Siegfried Map at different zooms to demonstrate the variability of size and shape of forest symbols, noise and complexity of map contents.

The above described graphics strongly intersect and overlap each other and are frequently closely spaced. This makes the map content extremely complex due to the graphics variability and density. The graphics exhibit a low quality compared to modern maps. For example the forest symbols are not closed circles, in most cases forest boundaries are frequently broken or merged with other map objects such as text, rock, roads, or forest symbols (Figure 6). Generally the lack of quality of the graphical representation aggravates the digital analysis of and extraction from the scanned map document. Specific problems are described in *Paper one*, in section 3.1 and in its summary in chapter 4.

2.3 Reference material

For a semantic investigation of the meanings of map contents in a historical topographic map reference data such as historical local maps, forest management plans, photographs, or reports from the same time are needed (Russell 1997). Aerial photography did not exist at that time, thus local reference data are the only sources of reference information. They are used in *study three* to more precisely define the forest concept and its variability, which has been derived by the perception-oriented approach. Based on cartographic rules, estimations of completeness and other features a definition of “forest” in the Siegfried Map can then be derived.

Communal maps at a scale of 1:5,000 or 1:10,000, which preceded the official cadastral mapping in Switzerland, already existed at this time and contained forest cover (Figure 7). Consequently, these maps can be supposed to be closer to the true state of reality and they still cover sufficiently large areas. The instructions for the data survey were much more detailed which allows the meaning of map contents to be investigated. It is important to keep in mind that the attribute meaning of forest might not be the same in both maps. The semantic difference between the two maps has to be investigated as far as possible for deriving a forest definition. However, important semantic features can be derived through a map comparison to formulate cartographic rules such as minimum area of considered forest patches or forest gaps.

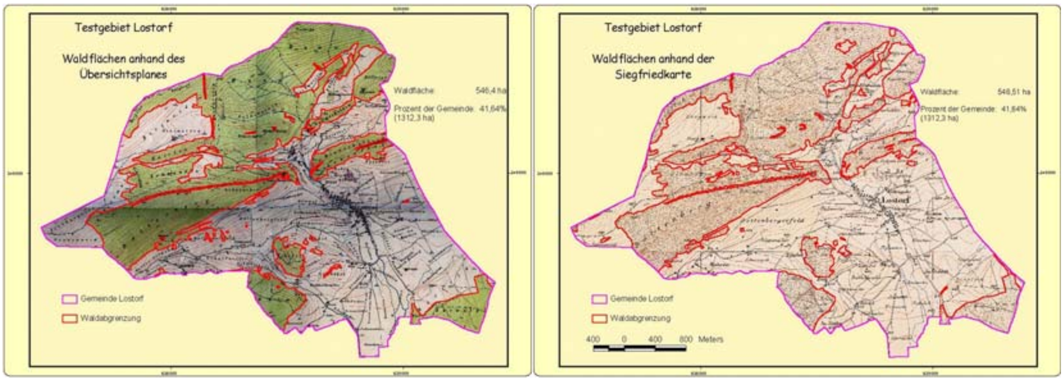

Figure 7. One example of a communal map of the political community of Lostorf (Canton Solothurn) which are used to evaluate the forest cover in the Siegfried Map, the spatial effect of uncertainty in study two and the semantic uncertainty in study three.

Historical photographs such as panoramic scenes (Figure 8) can be used in addition to the regional reference maps. They can be useful for verification of the map contents. For example, it can be verified whether avalanche tracks running through forest area are assigned correctly or whether small gaps and clearings in forest cover have been considered in the reference maps. Unfortunately, they are also very scarce for that time and hardly available for the same area for which reference maps have been found.

Other information sources for verification are local *forest management plans* and *forestry statistics*. In many Swiss Cantons, in particular in the Swiss Plateau, the cantonal forestry administration was already well developed and the needs for information about the area and the distribution of forests increased significantly (Grossmann 1949). In this context, the triangulation of the fourth order within federal and communal forests can be understood as a prerequisite for the preparation of management plans (Felber 1893). An abundance of management plans were produced between 1850 and 1890 based on cantonal instructions for forestry regulations (Puezer 1897). They are important results of forestry-related developments and represent a unique documentation of the history of forests and forestry in general (Schuler 1981). Within the mountainous region, however, these data sources are very scarce since the described developments in the forestry sector occurred here with a considerable delay for reasons which are named below. Forest statistics have to be read carefully since considerable errors occurred due to different methods used (Decoppet 1913).

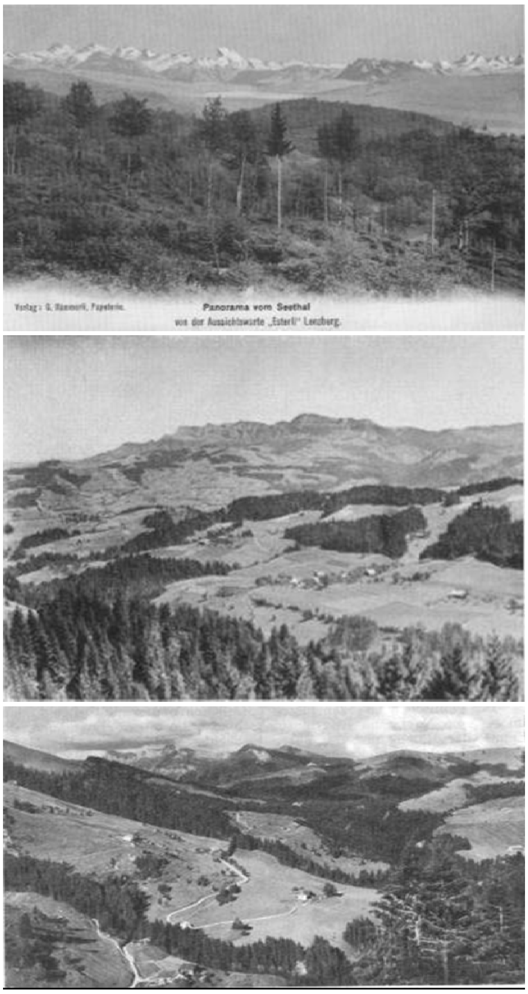

Figure 8. Historical photographs of forests in the 19th century are scarce and difficult to find; they can be used to reproduce the appearance of a “typical forest” in a particular region (top: Central Plateau, middle: Pre-Alps, bottom: Alps).

General background information about forests and their appearance in different parts of Switzerland during the 19th century can be found in an abundance of *reports of different forestry experts*. These reports are the results of federal and cantonal initiatives for the evaluation of the state and condition of Swiss mountainous forests. They have to be read carefully since they were motivated by the interests of the forestry lobby of that time (Richard 1999, Izeti 2001, Schmid 2001). Nevertheless, they provide important descriptions of the appearance of historical forests which are significantly shaped by forestry management systems and other uses. These historical documents are valuable sources to get an idea of what a topographer found during field surveys in the 19th century. Some examples of such reports are Kasthofer (1822) (described in Jenny 1952), Landolt (1862), Coaz (1889), Direktion des Innern (1898) or Kessler (1916).

2.4 Influences from forestry and politics

The lack in forest definitions in general and in the instructions for the Siegfried Map survey makes a comprehensive investigation of forestry related issues and other influences necessary. For a constructivist approach to landscape perception these influences have to be elucidated. The aim is to reconstruct step by step the situation of the topographer in the field influenced by these factors and to evaluate his attitude towards and perception of the forest. The concept of a forest is assumed to be the result of social constructions at that time (Table 2 in Paper two).

As mentioned above, the time of the initiation of the Siegfried Map field survey coincided with the beginning of modern forestry in Switzerland. Thus, there are important events in forestry, politics and agriculture as well as environmental issues to consider for a complete understanding of the attitudes towards nature and, in particular, forests. The development of the forestry sector during the second half of the 19th century was enforced by the rapid technological development and economic conditions. The increasing need for wood as a central resource (for railroad construction and the mining industry) and for agricultural land led to an overexploitation of the forests. In addition, non-timber forest uses such as temporary agricultural use or wood pasture were practised for long periods resulting in considerable damages to forest ecosystems (Stuber and Bürgi 2001). Consequently, a significant deforestation, especially in the Alpine region (Richard 1999), was observed. This was driven by the favourable economic situation on the wood market and the privatisation of woodland in the 19th century.

The beginning of federal forest legislation

The critical conditions of the mountainous forests and the occurrence of natural disasters such as the floods in 1834 and 1868, which were linked to the forest management practises in the Alpine region, led to fundamental changes in the Swiss forestry (Grossmann 1949). Federal initiatives started to enact a federal law for a sustainable forest management and the protection of mountainous forests. In the year 1862 Elias Landolt presented his report on the state of the Swiss mountainous forests (Landolt 1862). The intention was to put the forest legislation onto a scientific foundation and to prevent shortages in wood supply. This led to a growing consciousness of the protective function of mountainous forests. Similarly to Kasthofer in 1822, Landolt argued with simplified, publicly-oriented mono-causal relations (Richard 1999, Hürlimann 2004). The argument that deforestation had caused natural disasters, such as flooding, served as a political instrument to pursue federal forestry interests. In this context, public criticism against forest management practises in the Swiss Alpine mountains, in particular non-timber forest use and wood pasture, was expressed (Izeti 2001). After a second disastrous flood in 1868 and huge efforts in public relations and information and awareness campaigns, the forestry actors finally obtained great public attention. This attention was then used to the benefit of federal interests (Schmid 2001) and the first Swiss federal forest law was enacted in the year 1876. One of the main drivers was the Swiss Forestry Association (*Schweizerischer Forstverein*) which was founded in 1843.

The aim of this new law was to put an end to the effects of the insufficient legislation especially in the mountainous cantons (Landolt 1893, Henne 1939). Only in the Central Plateau and Jura regulations existed even though there was a considerable heterogeneity among them (Engler 1894). The first forest law aimed at the federal supervision of the federal mountainous forests and an end to non-timber forest uses and wood pasture (Bloetzer 1992, Stuber and Bürgi 2001, Bürgi *et al*. 2001). From this perspective this was the beginning of the debate about protection functions of forests and sustainable forest management in Switzerland.

Legislation-related consequences and potential conflicts

In reality, the new law had limited effects on the forest management practises in the Alpine region. It even carried a great potential for conflicts between federal or cantonal institutions and the autonomous Alpine communes (Nienhaus 2001). By law, the communes were obliged to abandon non-timber uses and wood pasture which people depended on. Farmers tended to declare forest used for wood pasture as agricultural land to pursue their own interests (Jugoviz 1908, Decoppet 1913). The new legislation aimed at the separate declaration of forest and pasture which meant that woodland used for pasture obtained the legal status of forests. In these declared federal forests non-timber uses and pasture were prohibited. This process was very slow and the acceptance of this law by the Alpine population remained extremely low. With the enactment of the second federal forest law in the year 1902 these efforts were pushed forward. Other important developments resulting from these processes were the stepwise conversions from simple coppice forests and coppice-with-standards forests to high forests (Bürgi 1999, Bürgi and Russell 2001). Furthermore reforestations were supported by subsidies, clear cuts were prohibited and sustainable management principles were introduced. The academic education of foresters was started at that time and in the year 1885 a forest research institute, the precursor to WSL, was founded.

Altogether the period of the initiation of the Siegfried Map field survey is characterised by significant changes in the public consciousness for environmental issues. The initiatives of the forestry sector aimed at making people aware of natural hazards caused by forest mismanagement and the protection functions of forests.

Parallels to topographic map surveys

Based on the presented historical information, only marginal parallels between the topographic field survey for the first edition of the Siegfried Map and forestry-related activities can be detected. Nevertheless, the need to combine them was expressed and obviously planned for later editions (Antiker 1927). This is also indicated by the introduction of the triangulation of the fourth order within the federal forests in the year 1878 (Schneider 1938), but the precision of the forest mapping was insufficient for the needs of forestry. However, the need for more accurate forest maps was a positive driving force for the production of communal maps which preceded the Swiss cadastral mapping (Brönnimann 1888). These are used in *study two* as reference maps. Forest definitions did not exist at this time. Topographers had the opportunity to use the symbolisation for *open* forest in cases where they could not identify *closed* forest. Thus the subjectivity in mapping forest was significant in both the thematic sense as well as with regard to the positional registration. The first forestry-related definitions were only introduced at the beginning of the 20th century (Schwappach *et al*. 1902).

2.5 Attitudes towards nature in the 19th century

In this section some aspects of the attitudes towards nature and landscape in the 19th century are described which are important for examining how forests were defined at that time. The forestry-related issues described above are extended for a better understanding of the societal situation and the general role of nature at that time. These considerations provide the basis for understanding the situation of the topographer and for evaluating the influences he was exposed to during fieldwork.

As mentioned above, the considered period (1850-1900) was characterised by drastic changes in connection with growing industrialisation, urban development, tourism and education. The human-nature-relationship at this time was dominated by a utilitarian perspective towards nature (Walter 1989, 1996). In Switzerland, long periods of overexploitation of the Alpine region by excessive cultivation led to a critical state of the landscape. This devastation and also the occurrence of natural disasters resulted in a growing awareness of the importance of nature. As described above by the example of forestry, public campaigns were initiated to make people aware of the need for nature protection by communicating the degradation of the Alpine landscape as the main reason for the occurrence of natural disasters. This protection was usually formulated as a protection of the population *against* nature or rather occurring disasters according to the anthropocentric perspective of the time. However, the attitudes towards nature changed in the course of a growing awareness that natural resources and threatened areas had to be protected to prevent further disasters.

In contradiction to the utilitarian view, the “return-to-nature” movement prevailed the aesthetic perspective on human –nature relationships of the time. Based on anti-urban ideologies conservative groups tried to highlight the increasing loss of identity (“Heimatschutz”) through socio-economic changes. They stressed the need for a harmonisation between people and the landscape. Nature and land were attributed with the symbolic meanings of stability and order. The activities of such groups aimed at preventing the increasing degradation of the Alpine landscape and defending the countryside against the “dangerous” forces of industrialisation and tourism. The contradictory dynamic of utilitarian and aesthetic perspectives can be seen as one essential element of the protective movement.

These developments are important for understanding the human attitudes towards nature in the 19th century. Particularly for this purpose the different and often conflicting perspectives of various socio-cultural groups have to be taken into account. In this sense, the meaning of landscape can only be defined from a contextualist perspective. From this perspective, landscape meanings are defined by time, place and history (Walter 1989). This means that, to understand how the topographers at the time perceived particular landscape elements, such as forests, one has to consider the variables which influenced their construction of meaning. Influences from politics, society, and economy have to be elucidated and the context in which the topographer was working has to be understood. This constructivist approach is briefly outlined in the next section.

2.6 The topographer’s perception of forest and the derivation of a forest definition in the 19th century: An outlook

The contextualist perspective explained above, considering the specific time, place and historical circumstances, represents the frame within which the individual perception of natural objects of the topographer in the field at that time must be examined. This individual perception is strongly influenced by external factors and norms from politics, economy and socio-culture, as well as the subjective values of the individual. According to the constructivist approach, lent from the social sciences, the meanings of landscape elements are understood as social constructions and are negotiable, often contested and thus relative. To understand the meaning attributed to forest during the fieldwork for the Siegfried Map, the influences that the topographers were exposed to, have to be elucidated in more detail. Thus the forest definition is understood as a social construction shaped by these influences as well as individual perceptions. Figure 9 shows a graphical overview of this approach.

Perception of forest and influences

Topographers in the 19th century were *educated* at academic institutions and thus had an advanced knowledge of the environment, climate, and other fields from the natural sciences. They were employed at *federal* institutions (e.g. the Topographic Bureau Berne) and had thus a certain commitment to federal interests. These facts indicate that topographers at that time were involved in the political debates of nature protection as described above. Due to their *proficiency* they were thus informed about ongoing changes regarding environmental issues and aware of small details within the landscape. Consequently, the group of topographers in the 19th century are assumed to belong to the part of the population that was aware of environmental issues resulting in a rather *aesthetic* view towards the landscape. As described above, there is evidence to equally defined interests from *topography* and *forestry* at that time. Even though forest *per se* has not been paid much attention to in official mapping instructions, one can expect that a topographer was aware of any kind of woodland in the landscape. Particularly, the triangulation of the fourth order within the federal forests indicated a growing importance of forests and their representation also in topographic maps. Nevertheless, at first, the topographic mapping was highly competitive among topographers in terms of "artwork" considering the beauty of a map. This beauty was measured by the aesthetic appearance of hachure and the newly introduced elevation contours.

The topographers found themselves in the crossfire of conflicting *economic* and *political* interests. On the one hand, they were obliged to assign forest area in the landscape, no matter whether it was used for pasture or not. On the other hand, the rural population felt threatened by such activities. Even if the topographers did not measure the forest area in great detail and no close link to forestry interests existing at that time, there was a deep distrust of federal employees within the Alpine population. Farmers were interested in declaring forest used for wood pasture as agricultural land. As described above, federal and forestry interests tried to stop all non-timber uses in federal mountainous forests by assigning the legal status of "forest" to them.

These are, roughly described, the main influences which could be of importance for the understanding of the meaning attached to forest from the perspective of the topographer at that time. To conduct a constructivist approach, suggestions have to be made for possible forest definitions according to the impact of these influences (Figure 9). This would result in a rather general, socially constructed term which expresses the assumed perception of forests from the perspective of a topographer. The aim is to elucidate the meaning attached to forest since at first glance forest seemed to be understood as a "self-explaining" landscape element which does not have to be defined in more detail. Historical photographs (Figure 8) and above described expert reports from the time in question can help to better understand what kinds of forest images the topographers found in the landscape and how they were shaped by forestry management practises.

Evaluation of identified and mapped forest representations in the Siegfried Map

After such a forest term has been derived, the semantics behind forest representations which are registered in the map have to be investigated in more detail. This is to understand what has been identified as forest and at the same time drawn in the field book. Here, the accuracy of the measuring method and the triangulation network, subjectivity introduced by the person in the field, and the above described forest terms have to be considered (Figure 9). Using reference data such as communal maps (*study 2*) and historical photographs, cartographic rules can be found which describe forest in the Siegfried Map by semantic and spatial characteristics. Some examples are minimum area of forest patches and clearings considered or the registration rate of avalanches. Furthermore, the use of the “open forest” symbolisation may be investigated.

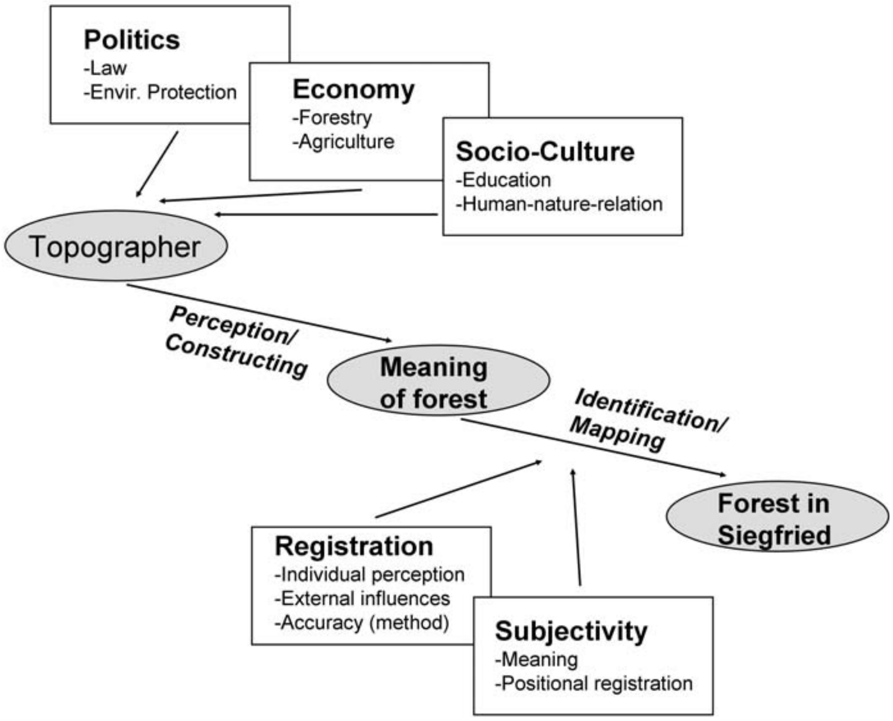

Figure 9. Overview of the constructivist approach to derive the forest image the topographer might have perceived to identify landscape elements such as forests or non-forests. Landscape elements can only be defined by considering space, time and history and thus from a contextualist perspective.

Considering the method, one has to bear in mind that in the Alpine region the original field maps of the Dufour Map were revised only, i.e. no complete surveying campaign took place. Thus it can be expected that the topographers did not fully access steep terrain for reasons of efficiency. Thus the quality of the forest cover mapping in maps of the scale 1:50,000 used in the Alps was found in some instances significantly lower than in maps of the scale 1:25,000 used for the remainder of the country. This is evident in all accuracy measures, the positional and the attribute accuracy as well as completeness. Consequently, this fundamental difference in reliability of maps of different scales and regions represents an important factor for understanding the semantics of forest representations. This leads to a bipartition of the analysis according to the two map scales and regions represented in the Siegfried Map.

<u>*Continuation of the approach*</u>

Altogether, a “topographic forest definition” has to consider all aspects which are described in this Chapter. The basic understanding of meanings attached to forest in the 19th century will be derived by the constructivist approach, supported by historical background information. Cartographic and semantic rules help to calibrate a semantic definition of forest which has been identified *and* mapped in the field.

The suggested approach requires significant efforts in continuing the historical investigation and the search for historical reference data, such as local maps or historical photographs. Future research has to be concentrated on the conceptual approach of perception and the calibration of semantic definitions based on the outline proposed. We believe that the combination of history, land cover change analysis and constructivist approaches of perception shows great potential for deriving semantic definitions of forest cover. Thus the amount of semantic uncertainty in a historical map from the 19th century could be explored to improve land cover change assessments.

Chapter 3

Theoretical background and key issues

In this chapter prevailing theoretical issues and current trends found in the scientific literature within the covered fields are reviewed. Central problems, key methods and concepts relevant to the contributions of this thesis are outlined, briefly, to position them within the corresponding research areas. Such aspects usually cannot be included into scientific papers due to the requirements of shortness and consistency. First, pattern recognition on maps is reflected and relevant research listed in Section 3.1. Here, specific problems are referred to and the concept of saliency used in Paper one is explained in more detail. Finally, some reasoning for decisions about specific methods is given. Uncertainty in a conceptual sense is dealt with extensively in Paper two. Therefore only some short comments are given regarding this issue in Section 3.2. Finally, some theoretical and methodological aspects of predictive uncertainty modelling (section 3.3) and fuzzy set based operations in the context of spatial analysis (section 3.4) are discussed. To avoid repetition, these considerations mainly touch on the decisions why certain methods are used, what particular advantages they have and what the particular problem is.

3.1 Pattern analysis and cartographic pattern recognition

Overview and specific problems

Cartographic documents contain valuable information for GIS-based applications and for many years research on automated feature recognition in maps has been conducted (e.g. Lichtner 1985, Kasturi and Alemany 1988, Samet and Soffer 1998). Frequent issues are text/graphics separation (Yamada *et al*. 1993, Cao and Tan 2002), segmentation (Centeno 1998, Levachkine *et al*. 2002), symbol recognition (Gamba and Mecocci 1999) or contour line extraction (Dupont *et al*. 1997, Khotanzad and Zink 2003). In many of these recent studies different approaches for automatic data capture and recognition from different types of maps have been demonstrated as well as the complexity (Dupont *et al*. 1997, Chen *et al*. 1999) and limitations (Ablameyko *et al*. 2001) of such tasks. Some examples of maps which have been investigated for recognition potential are the topographic maps of the United States Geological Survey (Li *et al*. 1999, Khotanzad and Zink 2003), the French national topographic map (Deseilligny *et al*. 1997), Chinese land register maps (Chen *et al*. 1999), the Bavarian cadastral maps (Mayer 1994, Maderlechner and Mayer 1995), the topographic maps of the Instituto Geografico Militare Italiano (IGMI) (Gamba and Mecocci 1999), and the present-day Swiss national topographic map (Stengele 1995, Frischknecht and Kanani 1998, Frischknecht 1999, Graeff 2002).

From the perspective of general symbol recognition, maps contain a high degree of complexity compared to other documents (Cordella and Vento 2000, Llados *et al*. 2002). This complexity is due to the dense representation of numerous map objects of different shapes or colours representing different objects in the landscape, text and their interaction. Watanabe (2000) proposed to define complexity by means of the individuality of the symbology of map objects and the correspondence among different objects. From this perspective a further differentiation can be made amongst the different types of maps where topographic maps are of highest complexity compared to cadastral maps or utility maps (Llados *et al*. 2002). According to this, procedures of pattern recognition applied to topographic maps have to solve complex problems. These are due to interaction, overlapping and intersection of objects, aliasing and false colours as well as ill-defined transitions from objects to the background (Khotanzad and Zink 2003). The severity of each of these problems depends on the quality of the considered map which is linked to the method of map production.

The first edition of the Siegfried Map, which is investigated in this thesis, was produced more than 120 years ago by copper or stone engraving. Due to its age and its manual production, the complexity, which is caused by problems described above, is significantly increased. The above mentioned studies mostly deal with maps of higher graphical quality and coherent colours defined for different objects such as lines or areas. Colours on Siegfried Maps show a high degree of variability, and false colours frequently occur due to aging effects. In addition there are significant differences between different map sheets making the data source extremely heterogeneous. These aspects are dealt with in a colour segmentation procedure which is simply based on radiometric thresholds and neighbourhood analyses. This works well for the segmentation of the considered group of map sheets in this thesis. To meet the variability of colours when considering larger amounts of maps this approach has to be further examined which is subject to future research. For the recognition process presented in Paper one the black layer is considered, assuming the successful conduction of colour segmentation in preliminary steps.

The objects of the black layer still carry a high degree of variability and complexity. The forest cover, which is part of the black layer, is represented by the spatial arrangement of individual ill-defined symbols, irregularly distributed throughout the area and boundary lines. Thus forest cover is represented by individual compounds. Boundaries are frequently coalesced with forest symbols and touched by other objects such as rocks or text (Figure 1 and Figure 4 in *Paper one*). Returning to the issue of complexity (Watanabe 2000), individuality of symbols to be searched is high due to a high degree of variability in shape and size. The correspondence between objects does not follow predefined rules, thus allowing frequent interactions between different objects and text regions of the same colour layer. It is altogether difficult to find studies in which a similarly complex problem has been solved or a map of comparable quality has been investigated.

The concept of saliency in multi-step recognition

Frequently one or more particular patterns are of interest in map recognition. In both cases the procedure immediately becomes very complex if interactions between different objects have to be considered and thus multi-step recognition procedures are proposed (Dupont *et al*. 1997, Khotanzad and Zink 2003). This is inevitable if the objects of interest cannot be detected by unambiguous characteristics immediately. For this reason in Paper one the concept of saliency (Rosin 1997, Smeulders *et al*. 2000) is introduced to facilitate systematic approaches and to determine appropriate methods for the detection of particular map categories in each step carrying salient features. Such a concept helps to understand the map content from the perspective of pattern analysis and to find ways to approach the objects of interest stepwise. Consequently, the concept is a useful approach if a simple extraction task is extended to a filtering process and can thus be seen as a map interpretation procedure (Watanabe 2000). Having identified the necessary steps, specific methods can be designed to meet the specific conditions in terms of robustness and recognition rate.

In Paper one saliency is defined as the existence of non-ambiguous features which allow the detection of a particular map category and thus the differentiation from other categories. In the context of multi-step recognition this concept is used to define a targeted process aimed at the detection of the category of interest in a stepwise fashion. Generally speaking, analysis based on salient features leads to sets of regions or points with known location and feature values capturing their salience (Smeulders *et al*. 2000). A similar concept has been applied in Rosin (1997) in the context of image retrieval. Salient features can be radiometric, colour or statistical discriminators as well as combined features derived from multiple testing and shape descriptors.

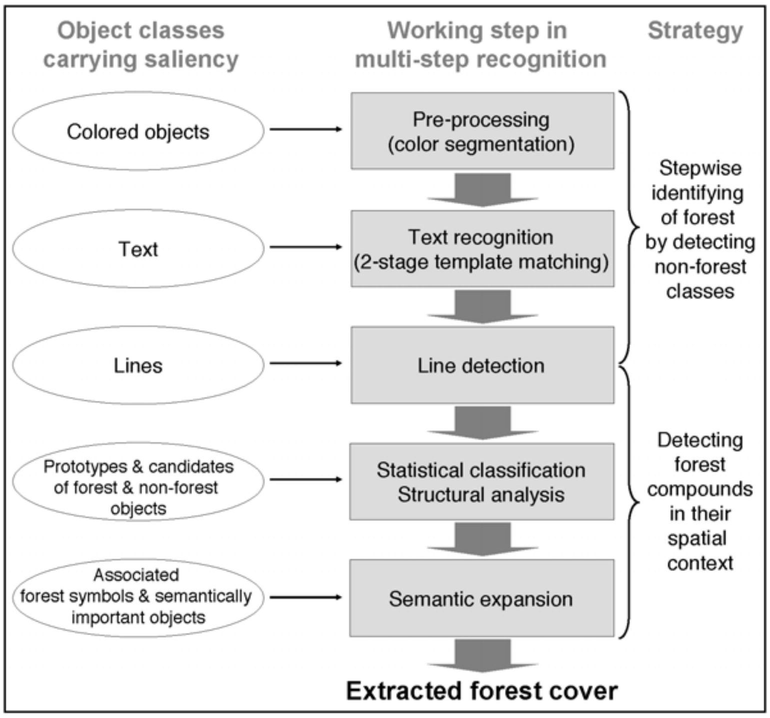

Figure 10. Overview of the working steps for multi-step recognition based on the concept of saliency. Text recognition and line detection are conducted based on salient features of non-forest categories to identify the forest objects step by step. Structural analysis uses saliency of forest prototypes as initial points to classify associated forest symbols. Semantic expansion follows semantic constraints to expand forest area in its spatial extent (from Leyk et al., Paper 1).

With regard to the Siegfried Map the high interaction rate and inherent complexity, as described above, did not allow the complete recognition of forest objects without the knowledge of and separation from all semantically important non-forest map categories. Thus the first idea was to find (non-forest) categories which impede the forest cover extraction but carry salient features. The purpose thereby was to identify forest cover objects in a stepwise fashion. At the stage where salient features could be found for detecting the forest objects themselves, recognition of forest cover could be conducted. In Paper one this concept has been applied to design a multi-step recognition process (Figure 10 and Table 1 in Paper one) which allows the extraction of forest cover in its spatial distribution. Thus, it represents a map interpretation procedure embedded within a bottom-up approach. The necessary steps in Paper one are text recognition or text/graphics separation, line detection, structural pattern analysis and semantic expansion (Figure 10). The methods are thoroughly described in the paper and a short literature review is given. Below only some short comments on these steps are given.

Text/graphics separation and text recognition in maps

Due to the use of stencils, text carries typical shapes which are used as salient features. Thus it was attempted to make use of this characteristic within a two-stage template matching procedure based on correlation. The basic idea of increasing the efficiency of such procedures by a pre-selection stage has been already applied in Vanderbrug and Rosenfeld (1975). The approach used in Paper one follows a different strategy for implementing two stages. Stage one aims at the recognition of shape prototypes which only occur in text but have to be found in each text region, using high correlation thresholds. “High” means that a high degree of similarity has to be found between the template and the map content before a shape prototype is registered. In the second stage only the local environments of these “anchors” are sought for the entire set of text symbols, allowing lower correlation thresholds (Figure 2 in Paper one). These lower thresholds allowed for registering text symbols for a lower degree of similarity between the templates and the map content. The analytical fundamentals of correlation-based template matching have been extensively described in Frischknecht (1999) and Graeff (2002). Other studies in which template matching has been tested successfully can be found in De Stefano *et al*. (1995) or Li *et al*. (1999).

Approaches in which use is made of short run length patterns (Myers *et al*. 1996), short strokes (Cao and Tan 2002) or typical features of character-like regions (Zhong 2002) were not applicable since they usually assume a higher graphical quality of the map. For the same reason methods based on feature points clustering and cluster compactness (Chen *et al*. 1999) could not be applied. Other approaches assume a low level of interaction between characters and objects (Deseilligny *et al*. 1995, Trier *et al*. 1996) and cannot be used therefore.

Line detection

The recognition of text regions is a prerequisite for the detection of line objects by salient features. Line detection as described in Paper one is based on inner dimension of objects (IDO). Linear objects are determined by combined salient features such as smoothness and minimum length of pixels chains, adjacency of line ends, slope equality of medial axes and offset tests (Figures 4 and 5 in Paper one). The procedure works in a similar way to line detection methods applied in other studies, such as Cao and Tan (2002), Chen *et al.* (1999), Khotanzah and Zink (2003) or Jinyang and Yumei (2004). In contrast to these studies the linear objects of interest – the forest boundary lines in the Siegfried Map – are extremely blurred and barbed due to coalesced forest symbols. This made it difficult to distinguish them from other line-like elements with sufficient robustness. Therefore the computation of the IDO index was implemented to facilitate the detection of the medial axis (Wolter and Friese 2000).

Structural recognition in maps
At this stage objects that portray information about the location of forest cover itself can be identified by conducting statistical classification, structural analysis and semantic expansion. Structural analysis (Pavlidis 1977, Delalandre *et al*. 2004) allows for deriving relational features to classify associated forest symbols. Therefore, forest symbol prototypes and candidates are iteratively tested for association within a larger group of similar elements (primitives) (Figure 6 in Paper one). The set of rules, describing contextual conditions such as distances and directions between the "primitives" (Myers *et al*. 1996) can thus be applied to find the amount of symbols of interest in the image (Llados *et al*. 2002). The hypothesis here is as follows. If a certain object, which has been classified as forest prototype, is detected, it can be expected that other objects, which belong to the same map category, occur close to that prototype (den Hartog *et al*. 1996, Ogier *et al*. 2001). Thus the entire group of forest symbols can be detected iteratively. This fundamental principle of structural pattern recognition could thus be successfully applied to the considered problem.

Semantic processing
Assuming the steps described above successfully enabled the classification of associated forest symbols, they can be used as starting points for semantic expansion. Here the semantics of all relevant classified objects in the map are considered (Cordella and Vento 2000, Dori 1999) to expand the forest area as defined by associated symbols and forest boundaries. This implies rules for crossing text regions and terminating the procedure at lines and rocks (Figure 7 in Paper one). A sufficient robustness of the procedure was shown in Paper one. This robustness is related to the fact that it keeps strictly to the associated forest symbols as initial points of semantic expansion. Thus the procedure represents a successful application example of semantic processing to cartographic pattern recognition.

3.2 Concepts and theory of uncertainty in GIScience

As mentioned above, uncertainty is the umbrella subject of this thesis. In Paper two the conceptual understanding and theoretical issues of uncertainty are considered. No conceptual framework has been found in the literature to solve the complex problem of uncertainty investigation in map-based land cover change analysis. Therefore, a framework for systematic investigation of uncertainty in such target applications is presented in Paper two. In recent years an abundance of contributions has been dedicated to the theoretical issue of uncertainty in spatial data from different perspectives. These research activities and existing links between them strongly influenced the development of the uncertainty framework. Therefore they are briefly described in this section.

Research on spatial data quality (Guptill and Morrison 1995, Aalders 1997, Veregin 1999, Shi *et al*. 2002, Shi *et al*. 2003) is generally related to the definition of metrics for reporting the characteristics of a product describing both the stated and implied needs of a user (ISO 8402). The desired objective is to link standardised quality reports with the assessment of fitness for use (Chrisman 1984, Aalders 2002). Different standards have been developed in recent years, e.g. Spatial Data Transfer

Standard (SDTS 1992) or International Organization of Standardization (ISO 2001), focusing on data production and the transfer of quality information.

Parallel to quality aspects considerable efforts have been made on uncertainty research in different fields such as GIScience (Burrough and Fank 1996, Lowell and Jaton 1999), spatial analyses in ecology (Hunsaker *et al.* 2001), remote sensing (Foody and Atkinson 2002) and historical cartography (Plewe 2002). Different contributions proposed definitions for uncertainty from slightly different points of view (Bennett 2001, Elith *et al.* 2002, Zhang and Goodchild 2002, Fisher 2003). Several authors proposed conceptual models or typologies of uncertainty in spatial data such as Beard (1989), Goodchild (1991), Fisher (1999, 2003) (Figure 11a), Gottsegen *et al.* (1999) or Morris (2003).

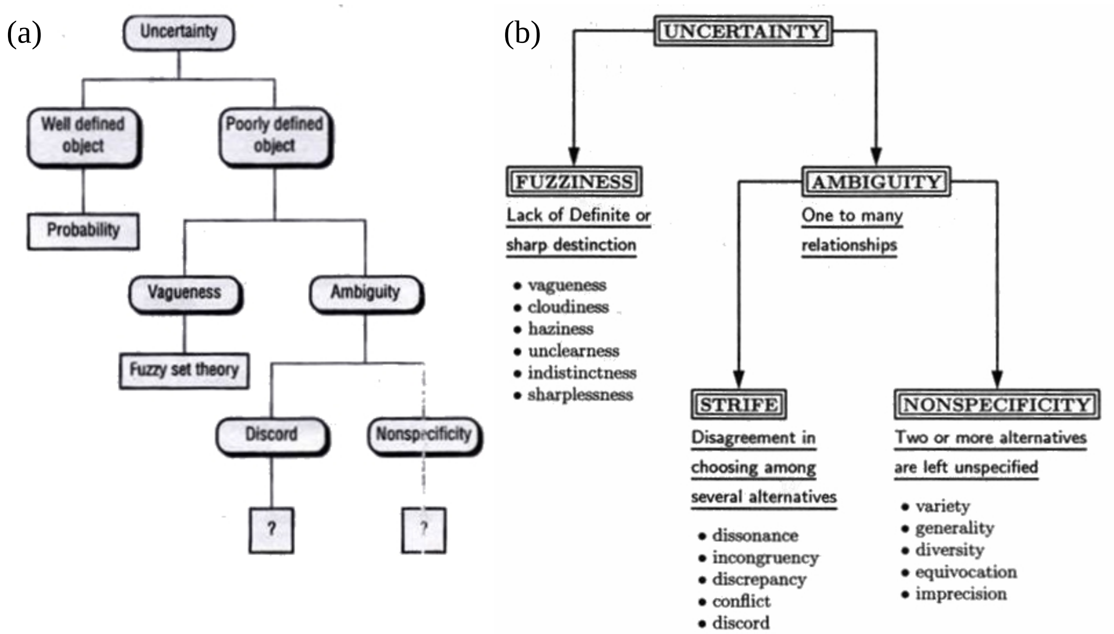

Figure 11. Conceptual models of uncertainty (a) from Fisher (1999) and (b) from Klir and Wierman (1999). These approaches strongly influenced the new typology of uncertainty which has been proposed in Paper two.

Such conceptual approaches, in turn, have been influenced by other scientific fields such as data quality, information theory (Klir and Wierman 1999, Figure 11b), philosophy (Tye 1994, Williamson 1994, Bennett 2001, Kulik 2001) or traditional accuracy assessment (Stehman 1999, Foody 2002). Fisher (2003) reports on parallels and discrepancies between research on spatial data quality and uncertainty (Figure 12). Data quality generally considers the production and transfer of spatial data and not its use (Veregin 1999, Fisher 2003). Since the use of spatial data represents an important potential source of uncertainty (Beard 1989, Gottsegen *et al.* 1999) it has to be included into conceptual approaches for a subsequent assessment of fitness for use (Agumya and Hunter 1997 and 1999, de Bruin and Bregt 2001).

Regarding these activities, a lack in systematic uncertainty investigation could be identified for using spatial data in target applications such as land cover change modelling. Therefore Paper two proposes a conceptual framework for uncertainty investigation in map-based land cover change analysis (Figure 3 in Paper two).

As will be described in the summary in Section 4.2, three domains are identified, which refer to *production-oriented*, *transformation-oriented* and *application-oriented* uncertainty. The basic idea for deriving these domains comes from the commonly used components of a GIS (Longley *et al.* 2002) which are *data acquisition, data handling* and *the use of spatial data*. Within each of these domains types or concepts of uncertainty are identified and appropriate methods for their assessment are proposed. A theoretical section in Paper two proposes definitions of these concepts such as ambiguity, error and vagueness to overcome the existing confusion over terms. These definitions are inspired by different fields as described above to find the most appropriate consensus. The result is a new typology of uncertainty (Figure 1 in Paper two) which is based on suggestions made by Klir and Wierman (1999) (Figure 11b) and Fisher (1999) (Figure 11a). Parallels between data quality elements and uncertainty concepts within the individual uncertainty domains are thoroughly evaluated (Figure 8 in Paper two).

Uncertainty	Data Quality	
Error	Accuracy	Positional
		Attribute
	Completeness	
Vagueness, Discord and Ambiguity ?	Semantic accuracy	
Error, Discord, Vaguness and Ambiguity?	Currency	
Discord	Logical Consistency	
?	Lineage	

Figure 12. Links identified between uncertainty research and spatial data quality reporting (from Fisher 2003), which has been extended in Paper two to examine parallels between data quality and uncertainty research in more detail.

3.3 Uncertainty modelling and prediction-based statistical approaches

Approaching the problem

Paper three is dedicated to the issue of uncertainty analysis and modelling. The motivation to find an analytical way to express uncertainty inherent in the Siegfried Map arose from the expectation that there was a considerable lack in mapping quality. This is particularly the case with map sheets covering the high mountains region of the Swiss Alps. The reason is intuitively obvious. As described in Chapter 2, in the high mountains the fieldwork merely aimed at the revision of the original field maps which had been produced during the Dufour Map field campaign. For this reason the efforts were kept to a minimum. Consequently, it could be expected that the harder the terrain became, the lower was the quality of the resulting map. To increase the reliability of land cover change estimations based on such maps, it was thus found necessary to identify and if possible even quantify these uncertainties. As mentioned, reference data were hardly accessible which meant that uncertainty could not be investigated for the entire area using references. Therefore, an approach was needed which allowed the prediction of uncertainty based on rules found in the few reference areas. Thus, the amount of uncertainty could be analysed in areas which are not covered by reference maps in a spatially explicit manner. This would be a prerequisite for the incorporation of the map in area-based land cover change models.

Traditional accuracy assessments or map comparisons which are frequently applied to remote sensing data (Foody 2002, Stehman and Czaplewski 1998) or cartographic representations (Fielding and Bell 1997) are useful to derive global summary statistics from confusion matrices. However, they do not allow any consideration of single entities due to a lack of spatial reference of accuracy measures (Foody 2002). Extensions of such approaches by fuzzy set techniques (Jäger and Benz 2000) also could not overcome this limitation.

Other contributions were much more interesting for Paper three. Lewis and Brown (2001) and Woodcock and Gopal (2000) presented approaches for area estimations from confusion matrices. This solved the problem of deriving area estimates from originally statistical accuracy assessments. Brunsdon *et al*. (2002) and Hagen (2003) used local neighbourhoods to derive local summary statistics. By this they provided an idea of how to express local accuracy as a spatially oriented measure. Finally, Steele *et al*. (1998) found some relations between topographical features and the accuracy in land cover maps. Despite these efforts, the problem of spatial prediction of uncertainty was not solved yet and accuracy assessments still limited to areas covered by reference data.

The idea to find relationships or rules between independent variables and the variable of interest at one study area and to use these rules for characterizing the same variable of interest within other areas leads to a classical modelling approach. Generalized Linear Models (GLMs) are traditionally applied for spatial predictions in habitat modelling in ecology (Austin 2002, Guisan *et al*. 2002) or econometrics (Anselin 2002). Some authors applied GLMs to inventory data (Moisen and Edwards 1999) or remote sensing based classifications (Schwarz and Zimmermann 2004). Thus in Paper three the problem was tackled by applying GLM's.

Independent variables which are supposed to carry predictive potential for uncertainty, or in this case mapping quality, are topography-related features such as elevation, slope or visibility but also distance measures from old road networks and forest boundaries as they are registered in the Siegfried Map. This set of variables is supposed to best describe the errors resulting from the historical fieldwork and thus uncertainty.

<u>*Designing the statistical model*</u>

The derivation of the dependent and independent variables and the mathematical formulation of the model are extensively described in Paper three. This section does not intend to repeat these issues but tries to highlight some important key features of the method with concentration on the dependent variable of the model.

Usually GLM's are used to predict the probability of presences based on a record of presence and absence data (Dobson 2002), e.g. of a certain species in habitat modelling. Logistic regression is then used to link the mean of the variable of interest to a set of predictors through a link function, in this case the Logit model. This allows the combination of predictors to be transformed to linearity and to maintain the final prediction values (after transforming them back) within the range of the original response (Guisan and Zimmermann 2000), usually between 0 and 1. This is meant by the statement that GLM's allow for non-linearity and are appropriate techniques if the dependent variable is bound (McCullagh and Nelder 1989). The fact that they do not force data into unnatural scales, allow for non-linearity and non-constant variances makes them very flexible for predictive modelling tasks.

So far, the model is a simple logistic regression applied to a different problem than usual. The key point to be emphasised is the derivation of the dependent variable. This is described in one subsection of Paper three. Here only some comments are given on this issue. Pixel by pixel comparison does not provide a representative uncertainty measure. The spatial unit would be too small and auto-correlated. Since distortion of the map is greater than one pixel, inherent uncertainty could not be assessed this way. Therefore spatially oriented measures of uncertainty had to be derived from a representative sub-area.

Here the idea of computing local map comparisons to derive local summary statistics within moving windows became interesting. Thus local Kappa or percent correctly classified (PCC) allowed the quantitative expression of mapping quality which can be interpreted as local uncertainty (Figure 13). The reason why these measures, which are continuous values from zero to one, can be used as dependent variable is that they are originally given in presence/absence terms from pixel by pixel comparisons. In this sense they are understood as weighted values due to their local environment. Advanced statistical software such as Splus allows for fitting the model with these values. This procedure allowed the calibration of the model based on spatially oriented representative uncertainty measures. The uncertainty expressed by these local statistics compensates for distortion and can be derived for any location in the map.

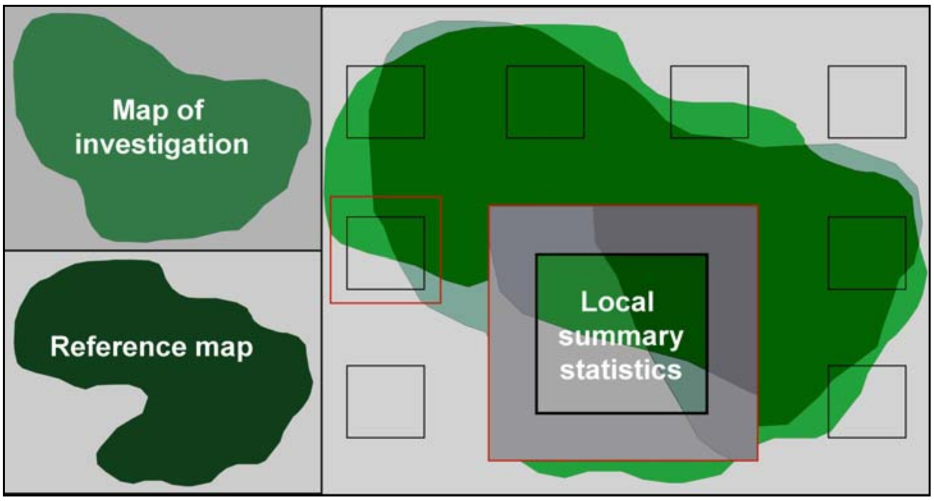

Figure 13: Illustration of local map comparison within local windows throughout the area to derive the dependent variable which has to be predicted by the model

The great potential of this approach can be seen at this point. The models proved to have significant predictive power. This means that uncertainty can be predicted within areas of similar conditions which are not covered by reference maps. This is interesting since knowledge of uncertainty at any position in a map opens a variety of possibilities to combine this approach with other target applications such as land cover change analysis. The model design is valid for any related application and can be easily implemented.

3.4 Possibilistic approaches and fuzzy set theory in GIS-based land cover change analysis and area estimations

In recent years fuzzy set theory has been widely used in GIS (Robinson 1988, Burrough 1989, Fisher 2000, Hagen 2003), remote sensing (Jäger and Benz 2000, Lewis and Brown 2001) and in classification accuracy assessments (Brown 1998, Binaghi *et al*. 1999, Foody 2002). Robinson (2003) provides a review on fundamentals of fuzzy set theory in GIS. In Paper four a thorough literature review of recent research is given. Also, a theoretical section is included which explains some fundamentals of fuzzy sets and fuzzy classifications (see Gopal and Woodcock 1994, Matsakis *et al*. 2000, Dubois and Prade 2000) as well as mathematical expressions. In this section some important aspects are touched upon to elucidate the chosen method and to emphasize the specialty of the approach in Paper four.

The purpose of using fuzzy set theory in Paper four is to convert the crisp classes, forest and non-forest, in the original historical map into fuzzy classes in which gradual transitions and multi-memberships can be defined. Since natural land cover classes are dealt with, such a data conversion is appropriate to overcome limitations of crisp sets in which locations only have either no or full membership (Woodcock and Gopal 2000). The conversion is done by defining fuzzy membership functions based on the predicted uncertainty measures of the predictive model presented in Paper three using the Semantic Import (SI) approach (Robinson 1988). Full use can then be made of continuous membership values between zero and one which come from truly predicted values. The known limitations of many studies can thus be overcome because fuzzy set values are not restricted to linguistic (Woodcock and Gopal 2000, Power *et al*. 2001) or categorical (Brown 1998) scales.

Defining fuzzy memberships and fuzzy classifications

The conversion of the modelled uncertainty or certainty values into fuzzy memberships is not trivial. This is due to the fact that certainty values reflect the local disagreement between two maps and are thus decreasing from both sides towards a local certainty minimum at boundary locations (Figure 14, Figures 5 and 7 in Paper four). Fuzzy set memberships have to be defined for any location to each class decreasing in one direction from full membership to one class to no membership of the same class. Locations of non-forest in the original crisp map close to the boundary still have fuzzy memberships to forest greater than zero and smaller than the certainty minimum at the boundary, and vice versa, for forest. Thus transition zones can be identified in which the entities have memberships greater than zero to both classes (Figure 14). The derivation of fuzzy memberships using some interpolated foot value surfaces is described in detail in Paper four (Equations. 4 and 5 in Paper four). The result is a possibilistic fuzzy classification (Gopal and Woodcock 1994) consisting of a fuzzy class for forest and one for non-forest (Figure 14, Figure **7** in Paper four).

Predictive bias reduction based on fuzzy memberships

These fuzzy memberships are used for a reclassification of the map in the next step. Other contributions such as Matsakis *et al*. (2000), Jäger and Benz (200) or Woodcock and Gopal (2000) presented different methods to improve classification accuracy using fuzzy sets. The aim in Paper four is to improve classification accuracy of the original crisp map by bias correction which is described in the summary of Paper four in section 4.4. Under the hypothesis that forest was underestimated during the object-driven historical mapping, different identification probabilities are assumed for forest and non-forest. Thus rules are defined for the reclassification process which favour forest depending on the level of certainty at the considered location (Equation. 6 in Paper four). This is done by including dynamic thresholds for certainty into the reclassification rules. If a membership of forest greater than zero is found at any location, forest is the more enforced the lower the certainty level is. A complete description of this process can be found in Paper four.

However, the gain in classification accuracy of the new crisp map has been iteratively computed for each threshold value between zero and one by crosswise testing between two independent study areas. If the thresholds, for which the improvement of classification accuracy is highest, have similar values in both areas, this would be an indicator for the predictive character of the entire analysis since the uncertainty values were truly predicted. Thus one specialty of the method is the link of a predictive modelling task with the map correction procedure which allows the application of the method to areas which are not covered by reference data.

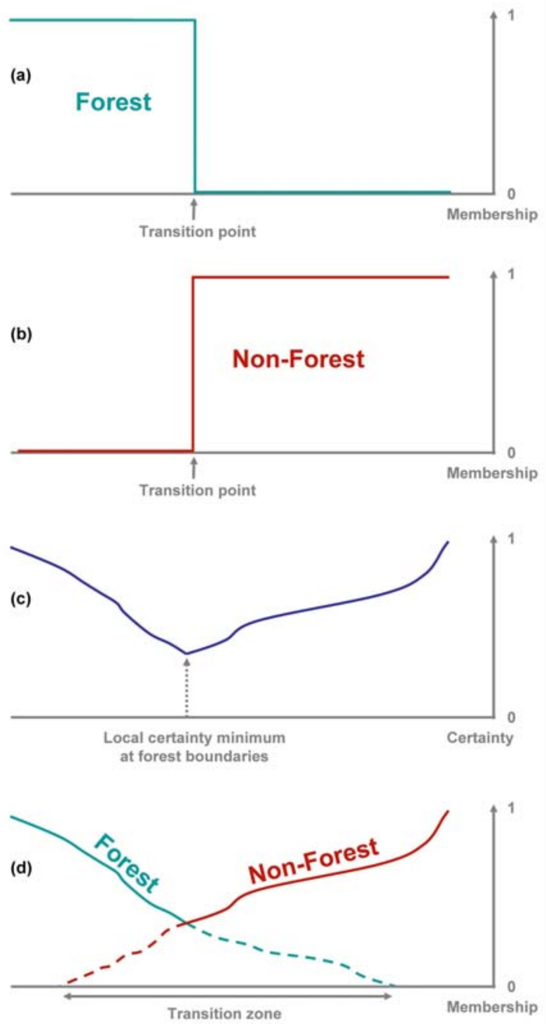

Figure 14. Illustration of the principles of the conversion of crisp sets forest (a) and non-forest (b) into fuzzy sets (d) based on predicted certainty measures (c).

<u>Advanced fuzzy area estimations</u>

Uncertainty based fuzzy membership values do not provide information about the area proportion within one considered pixel, as is frequently assumed in remote sensing data (Lewis and Brown 2001). Here the area of a fuzzy class is understood as a function of the alpha cut level (Fonte and Lodwick 2004). Briefly, it is the sum of all entities of one class which have a membership greater than or equal to the defined alpha cut level. Woodcock and Gopal (2000) present an approach for deriving more reliable area estimations dependent on the alpha cut level. They noted that for small alphas the area of a considered class increases and the sum of class areas can exceed the area of the map. This is related to the increase of transition zones and the number of entities with multi-memberships. Yet, the described approaches assumed that fuzzy memberships of one considered unit to different classes can be directly compared to each other. This assumption of comparability could lead to considerable estimation errors, i.e. if land cover classes of different characteristics are compared to each other. For this reason the described theoretical issue is expounded in Paper four.

New insights into spatial analysis and area estimation based on fuzzy set theory are provided. The basic idea in Paper four is to include the meaning of memberships of different classes into area estimations based on fuzzy set theory. It is expected that if these meanings are not the same, fuzzy area estimations based on alpha cut level only do not provide reliable results. In such cases, the difference between the meanings of fuzzy memberships to different land cover classes has to be accounted for. Paper four proposes one approach to solve this problem and examines the expectations described.

Chapter 4

Summaries of research papers

The research presented in this thesis is based on four research papers, as described above. In this section short summaries of each of these papers are presented. This is to provide a sound structure to this volume. The summaries do not substitute the reading of the full papers but provide a useful overview of the individual research packages.

4.1 Reading the map: Paper one

Leyk S, Boesch R, and Weibel R (in press) Saliency and semantic processing: Extracting forest cover from historical topographic maps. *Pattern Recognition*

4.1.1 Objective

This paper based on Study one reports on the extraction of historical forest information from the scanned Siegfried Map. The objective of this paper is to investigate the potential for automated recognition of the structural forest cover information. Thus the recognition process has to overcome a series of problems due to the low graphical quality of the hand-drawn map, high information density and intersections between features of the same colour layer. This process has to be sufficiently robust for the recognition of the forest cover which is represented by the spatial arrangements of forest symbols and forest boundary lines. The recognition of these patterns requires the consideration of intersected and overlapped features such as rocks, roads or characters to a high degree.

4.1.2 Methods

To meet the described problems and because forest could not be extracted directly a strategy based on salient features was developed. Salient features are characteristics such as colour, shape or statistical discriminators which occur in each feature of one searched category and in none of the other categories. Thus they allow for the unambiguous identification of one object category. Salient features can be single or combined characteristics. For this reason the strategy, based on saliency, aimed at a stepwise and systematic exposure of the information sought, by first searching for saliency of other object categories which impeded the detection of forest information but have salient features. If the forest patterns had been exposed, recognition methods could be applied to extract the forest cover in its spatial distribution.

Consequently, the first steps in which saliency has been used for detection were: *text recognition* by two-stage template matching based on correlation, and *line detection* based on sequential line tracking and continuation. For text recognition, salient features were defined by typical shapes of characters to be matched. Lines were sought based on combined features of smoothness, length and flow similarity of chains which relied on the medial axis.

After forest patterns were sufficiently exposed statistical classification provided prototypes and candidates of all relevant forest and non-forest objects. Structural pattern analysis based on iterative classification of forest symbols resulted in the identification of the associated forest symbols. Based on semantic constraints, attached to different object categories, and pre-defined actions a procedure of semantic expansion has been developed for final forest cover extraction.

4.1.3 Performance

The proposed recognition process is tested on a set of 1:25,000 maps dating from the same period of the first edition (1868-1875). The process proves to be robust (Kappa = 0.91 for the considered test samples) despite the expected recognition errors in character recognition and line detection. The reason for this is that it strictly keeps to the iteratively recognized associated forest symbols. Therefore errors in final forest cover extraction remain within an acceptable range and can be explained.

4.1.4 Main contributions

A robust process for the recognition of complex low quality representations of compositional map graphics is developed. The concept of saliency proves to be very useful for designing a systematic procedure to overcome the complexity of the map. Structural analysis and semantic expansion are shown to be appropriate methods for robust recognition of complex patterns. Consequently, a potential for the automation of this recognition process is demonstrated.

New variations in text and colours occur in maps, which were published 10 or 20 years later than the considered group. These variations have to be taken into account when applying the recognition process. Basically the system is dependent on the quality of graphics representations and on the results of pre-processing stages. Ongoing research will also be dedicated to point-based approaches of pattern recognition as an alternative concept to this area-based procedure. It can be expected that such methods efficiently extract and simulate survey-based information for larger regions.

4.2 Understanding the map in terms of uncertainty: Paper two

Leyk S, Boesch R, and Weibel R 2005 A conceptual framework for uncertainty investigation in map-based land cover change modeling. *Transactions in GIS* 9(3): 291-322

4.2.1 Objectives

Paper two is a part of Study two and tries to fill a gap in the conceptual understanding of uncertainty issues in the context of map-based land cover change modelling in GIS. The rationale of this paper is to develop a conceptual framework for systematic investigation of uncertainty in such target applications. A general validity of the proposed framework to similar applications using arbitrary kinds of historical survey-maps has to be demonstrated. This is done by applying the framework to the case of incorporating the historical forest cover from the Siegfried Map into forest cover change modelling tasks

The intention of this paper is to further the theoretical understanding of uncertainty, occurring in distinct forms or different types and arising from various sources. The framework aims at facilitating a systematic approach to the analytical treatment of uncertainty in its entire complexity. There are numerous links between research on data quality, error theory, uncertainty and traditional accuracy assessment. These activities result in a multitude of perspectives towards the same aspects and in a confusion of terminology. However, these perspectives have to be investigated to identify potential sources of uncertainty and to access its complex nature so that suitable concepts for its analysis can be systematically found.

4.2.2 The conceptual framework

The conceptual framework consists of three domains. In each of these domains the potential sources of uncertainty are systematically exposed and suitable concepts for its analysis are identified, as described above. For each concept, methods which are most appropriate for the quantitative or qualitative assessment of the corresponding uncertainty are proposed. They are briefly described in the paper in reference to the application example.

One domain of the framework is the amount of *production-oriented* uncertainty. This refers to the uncertainty which is inherent in the map. Frequently, this uncertainty cannot be assessed quantitatively for the entire area due to a lack of reference data or missing background information. Thus, the appropriate concepts are vagueness of definitions and ambiguity of land cover classes. The second domain refers to *transformation-oriented* aspects and considers uncertainty associated with different technical processes and transformations which the analogue and digital data were subject to. Since in this domain the assessment is repeatable, measurable and reproducible, uncertainty can be assessed quantitatively and error represents a suitable concept. Finally *application-oriented* uncertainty is identified as a third domain. It derives from the comparison of the historical map with newer data sources in the context of land cover change analysis. Here, semantically different data are compared to each other coming from different classification systems. Appropriate concepts for this domain are multi-temporal discord and equi-temporal ambiguity. The latter is counted as inherent uncertainty but affects this domain significantly.

4.2.3 Main contributions

The proposed framework facilitates the systematic understanding of the overall amount of uncertainty in map-based land cover change modelling. This amount is needed as a criterion for the assessment of the fitness for use (Agumya and Hunter 1997, 1999). The applicability of the framework is demonstrated with the application example where each domain was investigated separately. Its general validity for similar applications is stated as discussed in the paper.

Paper two represents an umbrella paper of this thesis since all other issues are part of this framework (Figure 4). The procedure presented in Paper one is linked to the domain of transformation-oriented uncertainty. Papers three and four both focus on the inherent or production-oriented uncertainty. Application-oriented uncertainty is touched on in Paper four where the aim is the improvement of land cover change analyses through uncertainty reduction.

4.3 Exploring the map: Paper three

Leyk S, Zimmermann N E 2004 A predictive uncertainty model for field-based survey maps using generalized linear models. In: Egenhofer M J, Freksa C, and Miller H J (Eds.) Geographic Information Science, GIScience 2004. *Lecture Notes in Computer Science* 3234: 191-205. Springer Verlag

4.3.1 Objectives

This paper, which is another part of study two, reports on the analytical evaluation of inherent or production-oriented uncertainty. Inherent uncertainty evidently associated with historical topographic maps from the 19th century occurs to a considerable degree. The interpretation of historical maps such as the Siegfried Map could be greatly improved by the knowledge of uncertainty and its variation over space. Unfortunately only few reference maps – usually local community maps – are available for that time. The objective of this paper is thus to establish predictive uncertainty models which are valid for the evaluation of any field-based survey map. These models should allow for the prediction of spatially explicit measures of inherent uncertainty in forest cover maps based on rules from several predictors.

4.3.2 Methods

In this paper Generalized Linear Models (GLM) and moving window techniques are used to establish predictive uncertainty models. GLMs are mathematical extensions of ordinary least square regression models. This approach is used to calibrate the model based on predictors derived in one study area for which reference maps existed. To test the predictive power of the model it is then applied to independent test data. Different topography-related variables and distance measures from old road networks and from registered forest boundaries in the Siegfried Map are expected to carry

predictive potential for uncertainty. It is hypothesized that the chosen set of predictors would best describe the errors of historical field work and hence the mapping quality.
The uncertainty measure, the dependent variable to be predicted, is derived from local map comparisons. At each position of the sample grid local summary statistics are computed by comparing the Siegfried Map and the reference map within the local windows of different sizes. The derivation of local Kappa coefficient and percent correctly classified (PCC) from these enlarged sample plots is expected to take the local distortion of the map into account. Hence, the procedure would allow an objective and spatially oriented comparison.

4.3.3 Results

Models fitted with uncertainty measures from 100 m windows best described the relationship to the explanatory variables or predictors. As the main result, the calibrated model shows significant prediction potential for local uncertainty. This is indicated by the deviance explained by the Kappa-based model of more than 40 percent. The correlation between model predictions and independent observations is $\rho = 0.76$. Consequently, an improvement of the model as compared to a null model to 47 percent, indicated by the G-value, is calculated.

4.3.4 Main contributions

Altogether the presented model allows for the spatially oriented prediction of inherent uncertainty within regions of comparable conditions which are not covered by reference maps. Nevertheless, the integration of more study areas is needed to define more general rules for objective evaluation of larger regions. It can be expected that regions of different conditions and topographic characteristics require modified versions of such models. The method presented can be applied for the evaluation of any field-based map which is prone to uncertainty.

4.4 Improving the map: Paper four

Leyk S, Zimmermann N E (submitted) Improving land change detection based on uncertain survey maps using fuzzy sets. Submitted to *Landscape Ecology*

4.4.1 Objective

Paper four is a direct continuation of Paper three. It presents a method for the predictive correction of classification bias in historical survey maps based on the knowledge of uncertainty from predictive models as described in the preceding paper. The objective of this paper is thus to improve the map accuracy and area estimations derived from the historical map and thus subsequent land cover change analyses. GLM-based predictive uncertainty models are thus to be linked to retrospective landscape assessments and land cover change modelling by using appropriate methods.

4.4.2 Methods

A fuzzy set based approach is proposed in this paper. Based on uncertainty information, fuzzy membership functions are defined to compute memberships for each location, in this example the membership to forest and non-forest, respectively. By this, the original crisp map is transformed into a representation of gradual memberships of each location to both classes. This is appropriate since forest represents a natural object and its boundary can be best described by gradual transitions to neighbouring classes. The result is a possibilistic fuzzy classification consisting of two fuzzy classes, forest and non-forest. Bias correction in forest area representations relies on the basic idea that inherent uncertainty was caused by an underestimation of forest during the historical fieldwork. This is linked to the assumption that different identification probabilities were attached to forest and non-forest in the field.

Sophisticated decision rules implying these identification probabilities as dynamic thresholds are formulated then to reclassify the fuzzy classification into a new crisp map of forest/ non-forest. The thresholds have the function of favouring forest as underestimated class during this transformation. Consequently, its area increases with an increasing degree of favouring. The optimal threshold is found iteratively by map comparison between the new crisp map and the reference map if the improvement of accuracy is highest. For a general validity of this predictive approach, the optimum of this threshold has to be similar for different study areas with similar topographic characteristics.

4.4.3 Results

The analysis, including the predictive modelling procedure from Paper three, is carried out pair-wise between two study areas to examine the truly predictive power of this approach. A significant improvement of the original maps due to bias reduction is demonstrated using similar thresholds. This improvement is indicated by an increase of the Normalised Information Criterion (NMI) from, e.g., 0.26 to 0.38 when comparing both, the original and the new map to a reference map. This finding is at the same time a proof for more reliable estimates of the area of fuzzy classes. The accuracy of land cover change assessments was shown to be improved by reducing the deviation from a reference change for almost 50 percent.

4.4.4 Main contributions

The combination of logistic regression techniques for uncertainty prediction and fuzzy set theory has been shown a successful approach for map improvement by bias correction. Area estimates and change detection based on the historical topographic map thus become more reliable for areas which are not covered by reference maps. The approach is valid for similar applications where maps, which are uncertain due to classification bias, are used. The approach has limitations if the original map shows already higher accuracy or lower classification bias.

Chapter 5

Discussion

The integration of map-based historical information in spatial analysis has a great potential for retrospective landscape assessment and land cover change modelling, the fundamental motivation for this thesis. The exploration and evaluation of historical maps such as the Siegfried Map has been identified as a complex and multi-facetted problem. With increasing age of the map, the complexity that must be dealt with can be expected to grow due to the lack of knowledge about the data source and its decreasing quality and reliability. This thesis presents a solution to a specific problem in examining the Siegfried Map as a potential data source for GIS-based spatial analysis. As a general issue, the thesis attempted to identify open issues within the research fields covered to further the scientific treatment of similar cases. A variety of limitations in map-based landscape assessments were identified. These are in general related to the availability of reference data, lack of data quality or the complexity of a specific subject.

Below, some important points of interest, gains, strengths and weaknesses as well as limitations of the individual approaches presented are discussed in more detail. For this analysis, the problem of information extraction addressed in Study one, is considered separately from the uncertainty-related issues which are related to Studies two and three. Here, in turn, the conceptual uncertainty framework is considered separately from the analytical part including uncertainty modelling and fuzzy set based map correction. Furthermore, the existing links between the single parts of this thesis are emphasised to elucidate their synoptic character.

5.1 The extraction of forest cover information from the historical map

In Paper one a multi-step recognition process for extracting the forest cover from the Siegfried Map is presented. This research has been conducted in the course of Study one (Figure 4) and aimed at extracting the complete area defined by the spatially distributed forest cover elements in the map. The extraction of the complete cover is a prerequisite for an area-based approach of land cover change modelling as described in Chapter one. In Paper one, the potential for the automation of such extraction processes was investigated. This has been motivated by the existence of more than

6000 map sheets of the Siegfried Map published between 1868 and the 1920s. Below weaknesses and strength of the proposed method are briefly outlined.

5.1.1 Gains and strengths

The proposed method provided robust recognition results demonstrated on several sample maps (section 4.1). Thus, problems related to the complexity and low graphical quality of the map, as described above, could be solved in general. During the structural analysis almost no classification error occurred. The semantic expansion procedure, in turn, keeps strictly to the associated forest symbols derived from the structural analysis. These symbols are the initial points for expanding forest area. The robustness of these two steps, structural analysis and semantic expansion, allows for minor recognition errors in text recognition and line detection. Thus a non-perfect performance of these first two steps can be compensated by semantic expansion. For line detection, the IDO index proved to be a suitable salient feature for searching line candidates by relying on the medial axis. The concept of saliency was shown useful to design a systematic strategy to approach the information sought and to determine appropriate methods for stepwise recognition. This concept is appropriate for similar applications in which multi-step recognition processes have to be applied.

5.1.2 Limitations and weaknesses

Though minor recognition errors in character recognition and line detection could be compensated to a certain degree, the occurrence of such errors indicates potential error sources if the method is applied to a greater amount of maps. The performance of the method depends on the comparability between the map graphics from different map sheets. This can be seen as one weakness in so far that a great variability of graphical representations has been observed amongst the complete set of map sheets. This is related to the fact that numerous map makers worked on the maps and each of them had an individual style and technique or even slightly different stencils. Furthermore, maps for the scale 1:50,000 showed a lower graphical quality than the maps at 1:25,000. Thus parameters such as correlation thresholds or distance measures, which have to be defined for different steps of the recognition process, have to be examined for their validity.

Several misclassifications of line-like rock portions as forest have been observed. The reason for this is the non-defined shape and structure of rock graphics in the map which occasionally results in line-like shapes. The consequence is a slight overestimation of forest area which usually can be neglected. Another weakness is the non-registration of forest area at locations where it is intersected by text regions. This kind of error cannot be prevented since the test for embedding of text cannot be approved and forest area is not expanded. Generally speaking, the recognition process is dependent on the graphical quality of the document and on the performance of the pre-processing steps.

5.2 The conceptual framework for uncertainty investigation

The Studies two and three are related to the issue of uncertainty. Thus Papers two, three and four as well as Study three (Figure 4) deal with different but complementary problems of uncertainty. In this section, an evaluation of the conceptual uncertainty framework developed in Paper two is provided. The topic of Paper two can be understood as an umbrella subject. The framework establishes links to all other papers and studies in this thesis (Figure 4) as has been already mentioned in the summary of Paper two in Section 4.2. This framework is thoroughly tested for its applicability to the problem of evaluating a historical map for use in spatial analysis. Below, the links between this framework and individual parts of the thesis are systematically described and comments on important points to each of these links are made.

A first link can be found to Study one (Figure 4). The automated extraction and other preliminary processes, such as scanning, are classical processing steps and transformations of the data. The amount of *transformation-oriented uncertainty* can be measured by an error assessment as presented in Paper one. The result is an estimation of the uncertainty introduced through these transformations and thus a measure of reliability for using the transformed or extracted data.

Attribute uncertainty or even semantic uncertainty, both of which are counted as *production-oriented uncertainties* in the presented framework, are investigated in parts of Study three making up the next link (Figure 4). The missing knowledge of the semantics of a landscape element causes uncertainty due to non-specificity. Study three shows that the derivation of a historical forest definition is a complex task touching different research fields. This part is also of special importance for application-oriented uncertainty where this historically "defined" forest is compared to modern data sources in which the definition for forest is different.

A next link can be found to Papers three and four (Figure 4). Here the spatial effect due to *production-oriented* or *inherent uncertainty* in forest cover is analysed and spatially predicted. Since uncertainty has been attributed to vagueness in definitions and ambiguities its quantification is difficult. Fuzzy set theory has been shown useful to overcome the limitations of crisp sets in accounting for gradual transitions and multi-memberships of entities which belong to natural objects.

Finally there is a link between the uncertainty framework and Paper four (Figure 4) where also *application-oriented* uncertainty is addressed. This paper is a methodological continuation of Paper three since the knowledge of uncertainty is used for map correction and thus for the improvement of forest cover change analysis. In other words, Paper four deals with reducing *inherent uncertainty* and at the same time with preventing *application-oriented uncertainty* when using the data.

5.3 Predictive uncertainty modelling and map correction

In this section Papers two and three, which can be seen as complementary issues, are considered together. The predictive uncertainty model developed in Paper three has been validated and further used in Paper four. The map correction procedure in Paper four was developed based on these uncertainty predictions. For this reason, the entire analysis described in Paper four is considered below, which automatically includes the subject of Paper three.

5.3.1 Gains and strengths

The predictive uncertainty model using Generalized Linear Models (GLM) ensures the spatial prediction of uncertainty for areas of similar topographic characters, which are not covered by reference maps. The model captured general trends of mapping quality as influenced by topographic and distance features. Thus the hypotheses formulated were found to be true in general and could be used to characterise the historical mapping process. The window-based technique allowed map distortion to be compensated and for the disagreement between both maps to be reflected spatially. The link between the predictive uncertainty model and fuzzy set based bias corrections was demonstrated successfully in Paper four. This approach is of innovative character to finally improve forest cover change models significantly as demonstrated in Paper four. The procedure reduces the classification bias, which is due to an underestimation of forest area for the reasons described in Section 4.4. Fuzzy membership functions are defined by truly predicted uncertainty values and weighted based on different identification probabilities. These weights generate an increase of forest area when transformation of the fuzzy values is made. Altogether the bias correction has been shown applicable to areas which are not covered by reference maps and thus the predictive character of the uncertainty model could be maintained.

5.3.2 Limitations and Weaknesses

Inherent uncertainty related to the historical definition of forest in the 19^{th} century could not be considered by this analysis. This is subject to the historical investigation which is described in Chapter two. This and some irregularities in the mapping process due to weather conditions or other individual factors are the reasons for a certain amount of unexplained uncertainty indicated by significant deviations of single observations. Furthermore, the map correction procedure has limitations if the considered map already shows a better accuracy as observed in one study area. Here, forest area underestimation has occurred to a lower degree. For this reason, only a slight increase in map accuracy was observed in this particular case. Basically, it was found that the map investigated must possess a minimum level of completeness regarding the representation of the searched for landscape element. This condition is fulfilled for forest cover information in the Siegfried Map.

This section provided a discussion of the individual contributions of the research papers by highlighting their gains and limitations. Therefore, these individual contributions were considered from a synoptic perspective to a certain degree. This perspective is maintained in the next chapter in which concluding remarks are made.

Chapter 6

Conclusions and Outlook

This thesis contributes to the fields of retrospective landscape research and uncertainty investigation in map-based spatial analysis. The overarching aim of the thesis was the evaluation of historical map-based information for its applicability to retrospective landscape assessments and land cover change analyses. Five research goals were formulated in response to five research questions as described in Chapter one. The intention of this chapter is to bring together the various issues by recalling these five research goals and to find an overall evaluation of them. First, the insights and outlooks are listed for the individual studies. Next, a synthesis is attempted by listing the main contributions of the thesis referring to the research questions formulated. Based on existing links between the individual studies a final evaluation of the application potentials for historical map data in landscape research can thus be given. The chapter ends with an overall outlook for future research.

6.1 Study one: Information extraction from the scanned map

6.1.1 Insights

Paper one examines the potential for data capture to be incorporated in area-based landscape change analysis, since the aim is the detection of the entire historical forest area. The method presented here allowed for the detection of low-quality structural information and the extraction of the spatial extent defined by the arrangement of the individual elements. Thus it can be concluded that there is a potential for automated extraction of forest cover from the Siegfried Map. To facilitate such a multi-step process and to find a systematic approach the concept of saliency proved to be a suitable strategy. With this strategy, the method could be designed as a targeted process to overcome the low graphical quality and complexity of the image. Its strengths are robustness, if the qualitative pre-conditions are fulfilled, the prevention of severe recognition errors, and the acceptance of recognition errors during the first stages of line detection and character recognition

To extend the process to additional map sheets larger knowledge bases of templates and scale-invariant methods of template matching have to be incorporated.

Furthermore, the method has to be examined for robustness when applied to the map sheets in the scale of 1:50,000.

6.1.2 Outlook

In the near future an alternative approach will be tested in which the relevant area of interest will be pre-selected at an early stage of the procedure. This will be done by classifying forest prototypes and candidates prior to text recognition and line detection to reduce the area needing to be searched in these two stages. Such an approach would result in an increase in efficiency. The disadvantage would be the specialisation of the procedure to forest pattern recognition. Furthermore, the implementation of rotated template matching methods has to be pursued to integrate rotated text in the recognition process.

Future research will also be dedicated to the evaluation of point-based approaches as described in the motivation section. Therefore, the local environment of each inventory sample point has to be examined by the recognition process to simulate the forest/ non-forest decision for the entire sample. Such approaches will imply the combination of semantic pattern recognition, spatial analysis and inventory statistics.

Also, colour segmentation processes, which meet the increasing heterogeneity in colours if a large amount of maps including maps of the scale 1:50,000 is considered, will be investigated. The threshold-based approach, which has been used in this thesis, will be extended by the computation of homogeneous regions and the application of region growing procedures.

6.2 Study two: Uncertainty investigation and modelling

Study two embraces Papers two, three and four. These contributions are considered in this section. Paper two is considered separately from Papers three and four which belong thematically together.

6.2.1 Insights

The conceptual framework for uncertainty investigation

The conceptual framework for uncertainty investigation has been proposed to the scientific community in *Paper two* as a theoretical contribution. Thus in the near future feedback is expected on whether this conceptual approach will be accepted and used by researchers within the GIS research community. The framework presented in Paper two facilitates scientific approaches of map-based land cover change analysis to identify the overall amount of uncertainty and to expose its potential sources in different stages.

The paper not only aims at encompassing the complexity of uncertainty, it also tries to further the theoretical understanding of uncertainty by identifying suitable concepts and analysis techniques within different uncertainty domains. It considers theoretical issues of data quality and error theory as well as uncertainty issues from other fields, such as information theory. The three domains of production-oriented, transformation-oriented and application-oriented uncertainty are intuitively understandable. Thus the framework tries to facilitate the access to the field of uncertainty investigation while maintaining a scientific approach. Considering the example of using forest cover from historical maps for forest cover change analysis, the framework proved to be useful for a systematic investigation of occurring uncertainty.

Predictive uncertainty modelling and map correction
The predictive uncertainty model in *Paper three* made use of historical knowledge and hypothetical expectations for the spatially explicit prediction of uncertainty. These expectations were related to the historical mapping process. As described, the uncertainty is understood as mapping quality. The model design was kept as simple as possible to ensure its general applicability to similar cases. The predictive power of the model could be assessed when tested against independent data. In *Paper four*, the same was done against independent data from another study area of slightly different topographic characteristics. This is an important prerequisite for applying the model to other areas of similar topography, which are not covered by the reference data

The approach allows predicting the uncertainty inherent in historical forest delineation in the Siegfried Map. The historical data source can thus be examined for reliability which is a prerequisite for objective map interpretation. It is concluded that GLMs are flexible tools for such spatial analyses.

An approach of incorporating the predicted uncertainty in spatial operations such as land cover change analysis is presented in *Paper four*. Predictive models are linked to a map correction procedure based on fuzzy set theory. The procedure was developed for cases where a map is inherently uncertain due to a classification bias which is the result of under- or overestimating one land cover class. The presented method allows correction of this bias and thus improvement in the subsequent land cover change models for areas not covered by reference maps. This has been demonstrated with one example. The use of different identification probabilities as weights in the reclassification step helped to produce new bias-corrected crisp maps. This provides important new insights in the use of fuzzy sets when the memberships at one location to different classes have different meanings. Thus the theoretical consideration was proven that fuzzy classes derived from object-driven mappings have to be weighted prior to a direct comparison. Area estimations become more reliable as indicated by an increase of classification accuracy of the new crisp map. It can thus be concluded that the area of a fuzzy class is a function of the alpha cut level and the threshold used for retransforming the fuzzy classification.

6.2.2 Outlook

The conceptual framework for uncertainty investigation
Future research should consider the continuation of the ongoing discourses of uncertainty. Theoretical issues will be further investigated to validate definitions for different uncertainty concepts which have been proposed in Paper two. Alternative techniques for uncertainty analysis in different domains of uncertainty have to be an integral part of ongoing research.

Predictive uncertainty modelling and map correction
The methods presented in Papers three and four should be further investigated for cases in which more than two classes are considered. Such uncertainty models would provide interesting insights into the past landscape including natural and artificial or anthropogenic objects. Future research should also be dedicated to the computation of the area of fuzzy classes based on the findings described above. The incorporation of these rules in fuzzy area operators could significantly improve the computation of fuzzy connectives applied to spatial data. Furthermore, the presented link between predictive models and fuzzy set based operations will be extended by additional

predictive variables such as visibility. Finally, testing effects due to spatial auto-correlation could be fruitful for the derivation of improved procedures.

6.3 Study three: Historical investigation

Study three was described in Chapter two. To date there is no research paper dedicated to historical investigation. Nevertheless, the preliminary results and the methodological outlook presented in Chapter two are the basis for ongoing research on this topic.

6.3.1 Insights

The historical investigation presented in Chapter two was carried out to further the understanding of the historical forest mapping in the Siegfried Map and the semantic meaning of forest area represented in this map. The aim was to derive a definition for forest used at the time of the map production since no definition *per se* was given in the topographical survey. This is a complex task which embraces different perspectives from history, politics, forestry and topography. One key actor is the topographer conducting the historical survey in the 19th century. This person was influenced by many factors at a time of marked changes in forestry, politics and society. To understand people's perspective on forests as natural objects, different contextual criteria have to be considered as presented in Paper two. Forest has to be understood as a topographic appearance at that time. Furthermore, special attention was paid to this landscape element at that time due to environmental hazards and propagandistic initiatives from the forestry sector. These influences shape the social construction of forest driven by institutional forces and group-specific perceptions of forest in the landscape. These political and socio-cultural constructions have to be considered when focussing on the group of topographers in the 19th century.

6.3.2 Outlook

Future research should continue in this approach to derive a historical forest definition for the time of the Siegfried Map, which is allowing complete assess of the domain of inherent uncertainty, as described in Paper two. At the same time, land cover change analysis, as presented in Paper four, becomes more reliable if the degree of compatibility between forest representations in different maps is known. Significant efforts to investigate the historical and social background involving researchers from different disciplines are therefore necessary to continue studies in this direction.

6.4 Main contributions: A synoptic view

6.4.1 Answering the research questions

In the conclusions made above, some important links between individual studies and/or papers have already been mentioned. In this section the different subjects are systematically brought together referring to the specific research questions (Section 1.4). Thus the overall issue is evaluated to answer the question of the applicability of historical topographic maps for more reliable retrospective assessment and land cover change analysis.

(I) *Can we develop methods of automatic and robust extraction of the forest cover information from the scanned maps to carry out an area-based approach?*

Paper one is dedicated to the fundamental *research question (I)* to examine possibilities for automated GIS data capture from the Siegfried Map. The multi-step recognition system represents a prototype for robust area-based recognition of forest cover which indicates a potential for automated approaches to extract the information for larger regions.

(II) *What is the suitable theoretical concept for the investigation of uncertainty in using the data for land cover change modelling and for understanding the individual components of uncertainty?*

Paper two presents a conceptual framework for uncertainty investigation in response to *research question (II)*. This framework facilitates the investigation of uncertainty in its entire complexity for conducting map-based land cover change analyses. Paper two furthers the theoretical understanding of uncertainty and suitable methods for its assessment. The framework has been applied in this thesis for the case of forest cover change modelling based on the Siegfried Map and proved to be suitable for similar cases. This conceptual understanding is considered as a prerequisite for answering the remaining research questions which are also related to the issue of uncertainty.

(III) *Are there ways to quantitatively assess inherent uncertainty at any location in a historical map and to predict its variability in space for areas which are not covered by reference data?*

(IV) *How can uncertainty information be effectively used for the improvement of map-based land cover change applications?*

In *Paper three*, which focused on *research question (III)*, an innovative approach to predictive modelling of inherent uncertainty has been presented. This approach is linked to a map correction procedure in *Paper four* in response to *research question (IV)*. These two papers together enable the assessment of uncertainty in areas which are not covered by reference maps and the use of this information for correcting classification bias. This improves both the retrospective landscape assessment and land cover change analysis.

(V) *Which historical definition can be assumed for forest cover representations in the Siegfried Map and can its semantic meaning be derived?*

Study three is an attempt to cover all relevant aspects needed to answer *research question (V)*. The derivation of a historical forest definition in the 19^{th} century was identified as a complex task. Valuable historical information about societal, political and economic influences and changes relevant to forestry and topography could be collected and an outlook for a perception-based approach was presented in Chapter 2.

As described above, the individual research questions, which make up important evaluation steps for the overall issue, could be systematically answered. Their synthesis thus allows for evaluating the applicability of the historical topographic map for area-based approaches of retrospective assessment and land cover change analysis. In this thesis, the complexity and multi-facetted nature of such an evaluation problem has been demonstrated with local and regional examples. Analytical ways have been presented for tackling the issues of extraction, reliability and uncertainty. Thus the application potential of the considered historical map for reliable land cover change modelling tasks could be examined and approved. At the same time, the thesis provides an overview of analytical steps which are necessary for ensuring a scientific approach of retrospective landscape assessments based on historical maps. The single methods presented have great application potential for similar problems due to a general validity and could thus contribute to the advancement in the respective fields.

6.4.2 Looking ahead

Future work will carry on the subjects presented in this thesis by testing the procedures for larger regions and by furthering the semantic historical investigation of forest definitions. Therefore more reference maps are needed. The area-based extraction of landscape information other than forest cover will be concentrated on to extend the considered number of classes for retrospective assessments and change detection. Alternative approaches such as point-based models for forest cover extraction and forest cover change analysis will be tested by the author in the near future. This approach would have the advantage that simpler extraction procedures can be applied to efficiently generate forest cover data for larger regions where the area-based approach has limitations. The basic idea would be the design of a retrospective national forest inventory based on uncertainty evaluation to derive statistical estimation parameters.

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Appendix A

Curriculum vitae

STEFAN LEYK

born June 09th, 1975, in Waren, Germany.

citizen of Waren, Germany.

Education

1990 – 1994	High school in Waren (Richard-Wossidlo-Gymnasium); “Abitur” obtained (preference in mathematics and science).
1994 – 1995	Civil service at German Red Cross, Waren.
1995 – 1996	Studies in Economy at the Technical University of Berlin and in Psychology at the Freie Universität Berlin.
1996 – 2002	Studies in Forestry at the Technical University of Dresden.
2000	*BSc Thesis.* Einsatzmöglichkeiten von Geographischen Informationssystemen im brasilianischen Amazonien im Zuge der Implementierung nachhaltiger Waldbewirtschaftungsweisen (Application potentials for GIS in the Brazilian Amazon in the scope of the implementation of sustainable forest management principles) at SUDAM (today ADA), Belem, Brazil and the Technical University of Dresden, advised by Prof. Dr. Michael Köhl and Dr. Benno Pokorny.
2002	*MSc Thesis.* Anwendung kombinierter Waldinventurverfahren auf Basis von E-SAR Daten im borealen Wald (Application of combined forest inventory systems on the basis of E-SAR data in the boreal forest) at Infoterra/ EADS Astrium, Friedrichshafen and the Institute of Biometrics and Informatics at Technical University of Dresden, advised by Prof. Dr. Michael Köhl.
2002	MSc in Forestry, Technical University of Dresden, Germany.
2002 – 2005	*Dissertation.* Title of thesis: Computing the Past – Utilizing Historical Data for Map-Based Retrospective Landscape Research. Dissertation at the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf and University of Zurich, Department of Geography, supervised by Prof. Dr. Weibel, Dr. Ruedi Boesch and Dr. Niklaus E. Zimmermann.

Part two

Research papers

Paper I

Leyk S, Boesch R, and Weibel R (in press) Saliency and semantic processing: Extracting forest cover from historical topographic maps. *Pattern Recognition*

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Saliency and semantic processing: Extracting forest cover from historical topographic maps

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Abstract

A multi-step recognition process is developed for extracting compound forest cover information from manually produced scanned historical topographic maps of the 19th century. This information is a unique data source for GIS-based land cover change modeling. Based on salient features in the image the steps to be carried out are character recognition, line detection and structural analysis of forest symbols. Semantic expansion implying the meanings of objects is applied for final forest cover extraction. The procedure resulted in high accuracies of 94% indicating a potential for automatic and robust extraction of forest cover from larger areas.

Keywords: Historical topographic maps; Cartography; GIS; Character recognition; Line detection; Structural pattern recognition; Semantic processing; Saliency

1. Introduction

Topographic maps are complex data sources with high information density consisting of symbols, lines and area objects to portray geographic and topographic information. Many objects represented on the map strongly interact, overlap and intersect with each other. These and other artifacts such as aliasing and false colors are the reasons for the complexity one has to deal with in automated pattern recognition approaches. This complexity is high compared to cadastral maps or utility maps [1–3], which typically contain machine-drawings of symbols and lines. Numerous recent studies have demonstrated different approaches such as segmentation [4,5], text/graphics separation [6–8], symbol recognition [9] and contour line extraction [10,11], for automatic data capture from cartographic maps. The maps used in these studies are of relatively recent dates. Hence, while they suffer from the above mentioned problems good graphical quality and thus well defined and regularly shaped objects can usually be assumed. Also, the area regions to be extracted are usually characterized by contiguous and homogenous colors such as green for vegetation.

In contrast to modern maps, historical hand-drawn maps present even more formidable challenges to automated data capture and object recognition, owing to the significantly lower graphical quality of the production and printing technologies of the time. Nevertheless, such documents contain valuable information about the historical landscape and are needed for GIS-based land cover change analysis. This is the main motivation of the presented research.

In this paper we describe the automated multi-step extraction of forest cover information from the so-called Siegfried Map, the Swiss national topographic map series produced during the final decades of the 19th century. The spatial representation of forest cover throughout the entire area of Switzerland before the advent of aerial photography represents a unique data source for research in landscape evolution, in particular forest cover change analysis [12]. The Siegfried Map consists of approximately 6000 map sheets published over 50 years, which illustrates the efforts of developing an automated approach. The difficulty of extracting forest cover from this data source mainly stems from its complex graphical representation of forest. It consists of

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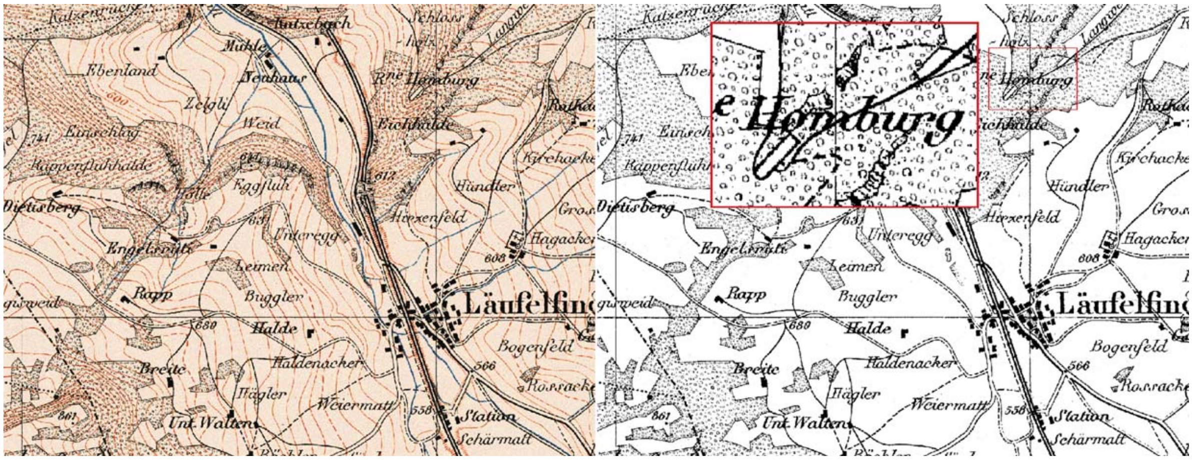

Fig. 1. The Siegfried Map (left) and the grayscale image which is the result of color segmentation.

irregularly arranged individual circular symbols and boundary lines which interact with other objects to a high degree, all of which are part of the black print layer (Fig. 1). The extraction of this high-level information is further impeded by the low quality of the historical map due to noise in color rendition, ill-defined shapes and varying sizes of symbols (due to hand drawing), as well as a high degree of overlaps and intersections between objects of the same color layer.

The remainder of the paper is organized as follows. In Section 2, the Siegfried Map and the representation of its graphics are described in more detail. Section 3 reports on specific problems compared to related work. The multi-step recognition process, which is based on the concept of saliency [13,14], is described in Section 4. The performance is presented on a group of similar maps in Section 5. Finally, conclusions are given in the last section.

2. The historical map and forest representation

The Siegfried Map (Fig. 1) was manually produced by copperplate or stone engraving at the scales of 1:25.000 in the Swiss Midlands and 1:50.000 in the mountainous areas, respectively. In order to render forest areas, map makers at that time engraved very small, thin graphical symbols closely spaced to each other by hand, yielding a stylized kind of tree pattern, surrounded by thin lines. Thus in addition to the radiometric noise in the scanned document there are a many closely spaced, overlapping and intersecting objects with ill-defined and noisy edges and boundaries. In this paper the “black” layer is considered and represented as 8-bit grayscale image (Fig. 1). Color layers for hydrography, contour lines and background were separated from the black layer by color image segmentation in a pre-processing step, which is briefly explained below. In addition to forests the black layer embraces the road network as solid, double or dashed lines, political boundaries, rock outcrops and cliffs, vineyards, buildings, as well as map text. Due to the low resolution of the documents these map objects strongly interact with each other. Since the extraction of forest cover is the aim, some characteristics of object categories relevant to the recognition process are listed below (Fig. 1):

- Forest is represented as a complex pattern (“compound object”), consisting of so-called “forest cover elements”. These are irregularly distributed circle-like small symbols (“forest symbols”), which are often not closed circles and forest boundaries for closed forest.
- Forest boundary lines strongly vary in width and have ill-defined or blurred transitions to the background, frequently broken or interacting with other objects such as forest symbols.
- Text regions in different styles, sizes and orientations frequently overlap and intersect with forest. Characters of the smallest category are connected and have line-like widths. Due to stencils used, text shows some regularity in size and shape.
- Outcrops and cliffs have no pre-defined structure, shape or size resulting in a high degree of representation variability. “Rock” is represented by larger dark regions and line-like sections.

3. Specific problems and related work

Several studies, which aim at the recognition from cartographic maps, can be found. In the following a brief review of related research is given and the used methods are evaluated for their applicability to the considered problem.

Some approaches of *text recognition*, applied to maps, make use of patterns of short run length [15] or short strokes [6], feature point clusters and their compactness [7] or other typical features for character-like objects [16] to isolate them from lines or other graphics. Since the connected characters of the smallest category in the Siegfried Map have line-like width, such approaches unfortunately do not allow the separation of characters from shorter line segments in forest boundaries or rock. Template matching, in turn, is a well-known method for character recognition applied to noisy images [17]. It is successfully tested in Refs. [18–20] on maps, which are of machine quality.

Some of the above mentioned studies aim at the detection of *lines* from thinned images after text has been separated. In Ref. [6] line continuation based on similar slopes, adjacency and size measures is tested. Graphical line tracing based on tests for slope equality and offset is applied in Ref. [7]. Since forest boundary lines in the Siegfried Map are extremely blurred and jagged and rock also features line-like strokes, reliable line detection has to preserve these structures forbidding a priori thinning. Due to the high degree of coalescence between map objects, forest in the Siegfried Map is not featured by regular shapes or even polygonal approximations. Thus Hough transformations [8] cannot be applied for line detection. Some studies focused on the extraction of contour lines [11] or roads [21] mostly relying on well-defined line segments.

Structural pattern recognition [22,23] is based on the definition of spatial relations between graphical “primitives” (context) such as distances and directions. The resulting set of rules is applied to find the symbols in the image [2,15]. Some related work can be found in Refs. [24,25], where contextual reasoning is used to find certain types of objects in the vicinity of an already recognized object. Since forest cover in the Siegfried Map is represented by a complex pattern (Fig. 1), structural analysis is an appropriate method to define the spatial extent of forest.

4. Methods

Due to the inherent complexity of the graphical map content as described above, forest cover elements cannot be extracted immediately and directly. Therefore this paper proposes a multi-step recognition process based on saliency [13]. The basic idea is to search for non-ambiguous non-forest objects, which can be detected with color or shape discriminators, first, to identify forest cover elements step-by-step until these elements can be directly detected. The concept of saliency and the methods to be applied in each step are described in detail below.

4.1. The concept of saliency and its application to multi-step recognition

One pre-condition for the unambiguous identification of relevant non-forest objects, which intersect with forest in the map, is the existence of salient features that can be used by recognition methods. Forest cover elements, which are sufficiently isolated and unambiguously described by salient features themselves, can then be directly extracted.

Generally spoken, analysis based on salient features, which has been applied in Ref. [13] in the context of image retrieval, leads to sets of regions or points with known location and feature values capturing their salience [14]. Here, *saliency* represents an umbrella concept and is defined as the existence of non-ambiguous color or shape features attributed to each object of one particular map category, which do not occur in all other categories. Such features would allow for explicit detection of the complete set of objects of the considered map category. This concept is used in this paper for designing a systematic (targeted) multi-step recognition process (Fig. 2).

The first categories, which can be detected using salient features, are the color layers in the map. *Color segmentation*, which is considered as pre-processing step and thus not further explained in the methods, is based on HSL-thresholds for each layer. Color seeds are identified and propagated by evaluating measures of color homogeneity between neighboring pixels. Similar to Ref. [5], the final decision of belonging to one layer depends on geometric constraints such as the minimum size or length of a homogeneous tested local color region. The result of this step is the isolation of the black layer and its representation in a grayscale image. In this image text is the most interfering map category, which follows weak rules due to stenciling, at the same time. Thus typical shapes in the text are used as salient features to carry out *text recognition* based on two-stage template matching aiming at the identification of all text regions. In a next step combined salient features of lines are searched for. A robust *line detection* procedure based on the medial axis and tests for length, adjacency, and flow similarity of lines is proposed. *Statistical classification* [26] and *structural analysis* based on relational features and connected components are then applied to identify candidates and prototypes of forest and non-forest map categories. Finally, *semantic expansion* based on class-specific semantic constraints, search rules and termination criteria is carried out [27]. Table 1 and Fig. 2 illustrate the recognition process based on saliency.

4.2. Text recognition by two-stage template matching

A two-stage template matching procedure based on cross-correlation [28] is applied to the 8-bit grayscale images, which feature the black layer and background, aiming at the recognition of horizontal text regions of the smallest category. To reduce computational effort, relevant regions were pre-selected by simply assessing the number and density of non-background pixels within a local window. The size of the window depends on the size of characters investigated, which is between 10 and 25 pixels height (Fig. 3b).

In the first stage, salient abstract “shape prototypes” such as the “u”, “o” or “n” shapes (Fig. 3c), which only occur in text but where at least one of them can be found in each text region, are searched for throughout the pre-selected regions. This effect of similar shapes has been also used in Ref. [18]. For example, the n-shape allows finding “n”, “m” or “h”, the u-shape “u” and typical connections between characters,

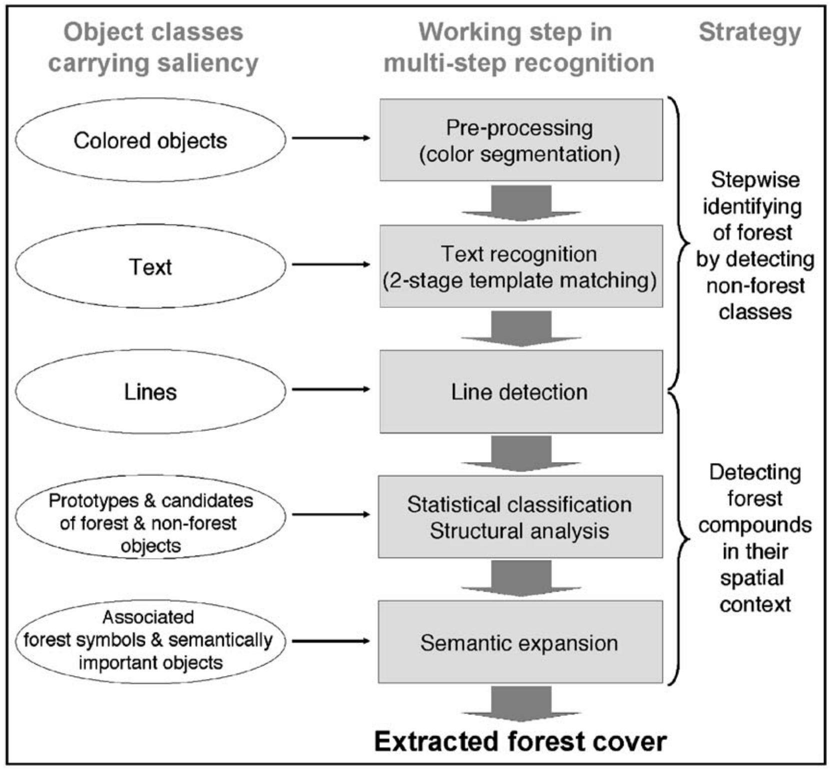

Fig. 2. Flowchart of the multi-step recognition process based on saliency for forest cover extraction.

Table 1
Overview of the methods used for multi-step recognition of forest cover elements based on saliency

Object categories	Salient features	Step	Result	Relevance for exposing forest	Image depth
Color layers	Colors	Pre-processing	Separation of color layers	“Black” layer including forest	24 bit
Text	Typical shapes in text regions	Two-stage text recognition	Recognition of text regions	Text/forest graphics separation	8 bit
Line objects	Combined line test descriptors	Line detection	Line segments	Forest boundaries as part of the set of lines	IDO, 8 bit
Forest symbols	Relational features	Structural analysis	Identification of relevant classes	Associated forest symbols (inner forest)	CC and pixels
Forest cover	Semantic constraints	Semantic expansion	Forest and non-forest pixels	Extracted forest cover	Indexed

etc. For the recognition of numbers the set 2 to 10, except 7, is included. Each template consists of black text values (foreground), white background, and a region of values to be ignored during processing to describe abstract shapes and to compensate inclination. The prototypes are sought for in connected and inclined characters for high correlation thresholds. The identified prototypes are then marked in the image (Fig. 3d).

These marks are the initial points for matching the entire set of horizontally oriented characters and numbers in the second stage. The pre-selected regions for starting points of the matching procedure are further narrowed in. Horizontal corridors are defined with lower and upper bounds based on the position of the marked prototypes. Left and right margins are defined by the pre-selection of stage one (Fig. 3e). The templates are partitioned in character, background and ignored regions to compensate inclination. In stage two lower correlation thresholds are used than in stage one since the risk of misclassification is limited to the preselected regions (Fig. 3f). Rotated and bended text rarely occurs in the map (4.2% and 1.8% in forest area). For this reason and to keep the entire process to a manageable complexity, rotated text is not recognized. This text is expected to be partially classified as isolated line segments by line detection and smaller remaining regions by the classification procedure both of which will be tested for embedding in forest area as described below. Thus the error expected due to these misclassifications is negligible. Nevertheless, rotated text should be considered using rotation invariant recognition methods [18,29] if the maximum of extraction

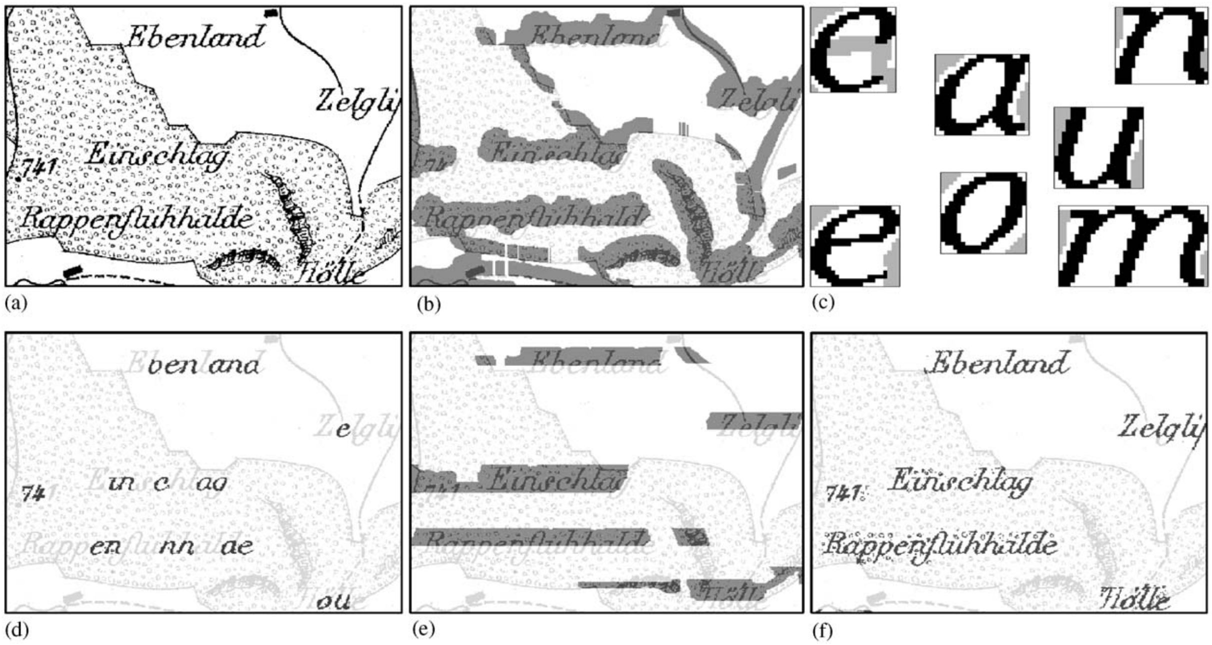

Fig. 3. Text recognition by two-stage template matching. (a) Gray value image. (b) Pre-selection for stage one. (c) Shape prototypes for matching in stage one. (d) Matched shapes in text (stage one). (e) Pre-selections for stage two. (f) Final result of text recognition.

accuracy is required. Characters of larger sizes (Fig. 1) are matched immediately by only one stage since their shapes are sufficiently distinct and thus salient.

4.3. Line detection

The recognition of text allows formulating and testing combined salient features for lines in the map. Line detection has to be robust enough to detect blurred lines of varying widths since any line in the map could be a forest boundary. Furthermore, the procedure has to detect lines with a high number of dangling line ends due to the coalesced forest symbols and to differentiate them from line-like parts in other objects such as rocks. The coordinate lines are first identified by global criteria indicating the frequency of black pixels in one column or row relative to the vertical and horizontal map extents, respectively. In the following IDO image transformation, determination of line candidates, sequential line tracking and line continuation are described.

4.3.1. Inner dimension of objects (IDO) image

In a preliminary step the black layer is transformed into a representation of the inner dimension of objects, called the IDO image. Only true object pixels (black) are considered to prevent disturbances through ill-defined transitions to the background. The IDO index of a black pixel remains zero if there are less than eight black neighbors in its direct eight-neighborhood. A dimension index of one indicates a full black eight-neighborhood. This index is further incremented if each of these black neighbors has a full black eight-neighborhood itself (Fig. 4a). For line detection only

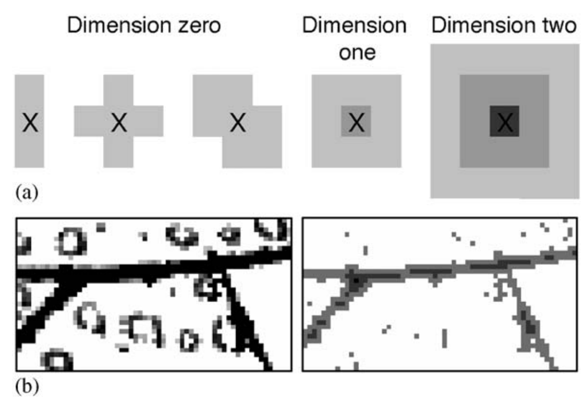

Fig. 4. Principal concept of the inner dimension of objects (IDO) image. (a) The IDO index of a black pixel ("x") is equal to one if it has a full black neighborhood and further incremented if the neighbors have full black neighborhoods (IDO = 1) themselves. (b) An example of IDO image transformation.

pixels of index zero, one and two are of interest (Fig. 4b) to consider lines of various widths. These transformed IDO indices feature the true inner dimension index of each pixel and allow thus the estimation of the position of the medial axis of line-like objects (Fig. 4b).

4.3.2. Identification of line pixel candidates

Line candidates are defined in the IDO image (Fig. 4b) in a first step as follows:

- Pixels of IDO equal to two, one or zero are tested for elongated eight-neighborhoods, indicated by gradients towards lower IDO or background in two opposite directions

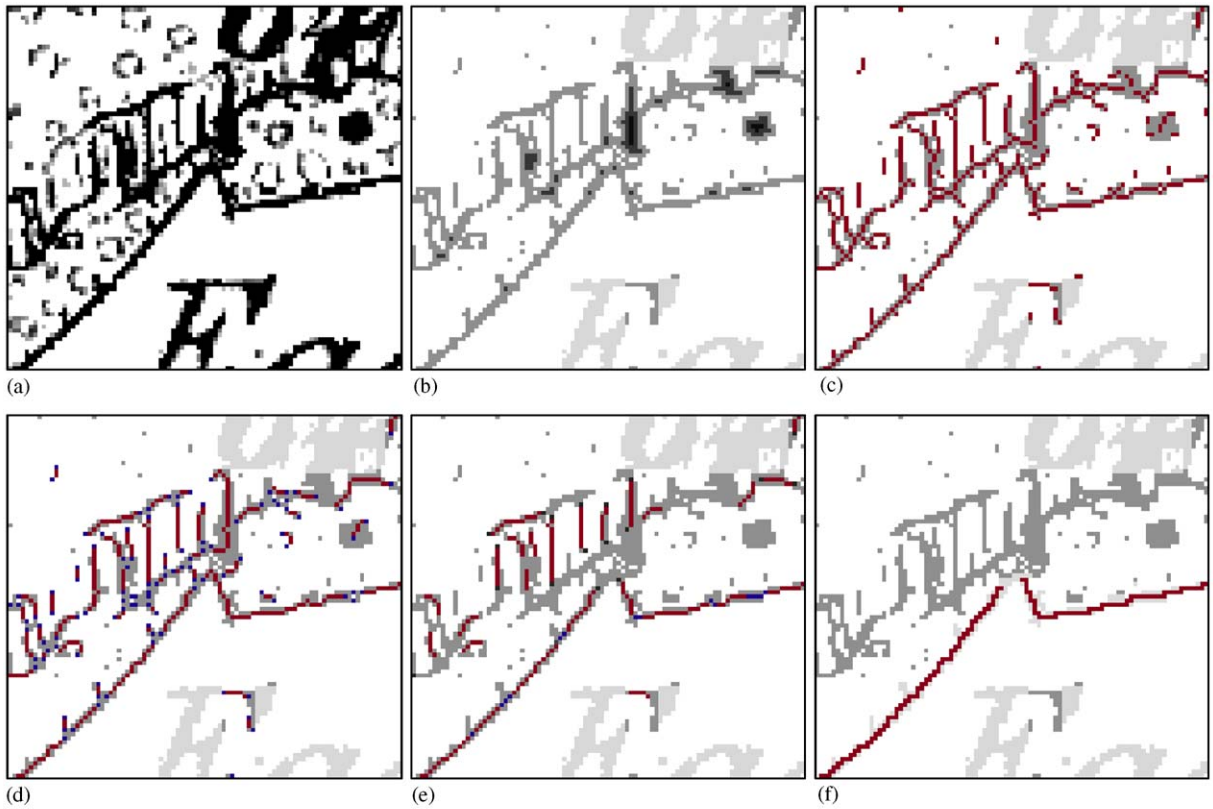

Fig. 5. Line detection. (a) Original gray value image. (b) IDO image. (c) Line candidates based on IDO index (red). (d) Eight-connected chains after crossings are deleted (red) and new line ends (blue). (e) New connectives between lines (blue) after flow similarity testing. (f) Final connected line segments (red).

and equal or similar IDO in the other two perpendicular directions (Fig. 5c).

- Pixels of the highest IDO (2) are examined first, the lowest one at the end. If a black pixel has less than eight black neighbors the most central one is examined first.

The procedure strictly relies on the physical center line, whatever the width of the considered object is. Thus it represents the medial axis of the line segments as the center of the maximal disk in the original shape [30,31]. If a candidate is identified, it is marked to prevent local accumulation of candidates if neighbors of lower IDO indices are considered. The identified candidates are converted to eight-connected neighbors. Each candidate, which has one, two, or more than two neighboring candidates, is registered as line end, line connective, or line crossing, respectively. Line crossings are then deleted and their neighbors are registered as new line ends (Fig. 5d).

4.3.3. Sequential line tracking

The identified chains of line candidates are further examined to identify line segments in the IDO image. Therefore sequential line tracking is applied, as follows (Fig. 5d):

- Tracking starts from any line end and chains of line connectives are tracked.
- A connective is added to a chain only if local smoothness is acceptable (i.e., no abrupt changes in direction occur).
- Tracking is terminated if a line end is reached or an abrupt direction change occurs. The length of the chain is registered, the position is marked and in the case of abrupt direction change, the next neighboring connective is converted to a new line end.
- The procedure runs until no more line end is found in the image to start with.

The tracked chains are categorized by length into three classes. Chains of a length, greater than the maximum length of line strokes within rock are immediately assigned a line segment (category A). Shorter chains are potential line candidates to be examined in the next step (category B). Strokes, which have a length smaller than that, required for category B, are converted to black (category C).

4.3.4. Gap filling and line continuation

The identified line segments and candidates are further examined for flow similarity to test whether two segments belong to one line and to identify false line chains (Fig. 6). The procedure, which is described in a pseudo-code (Table 2), starts from end points of line segments of category B (Fig. 6). The following conditions have to be fulfilled to

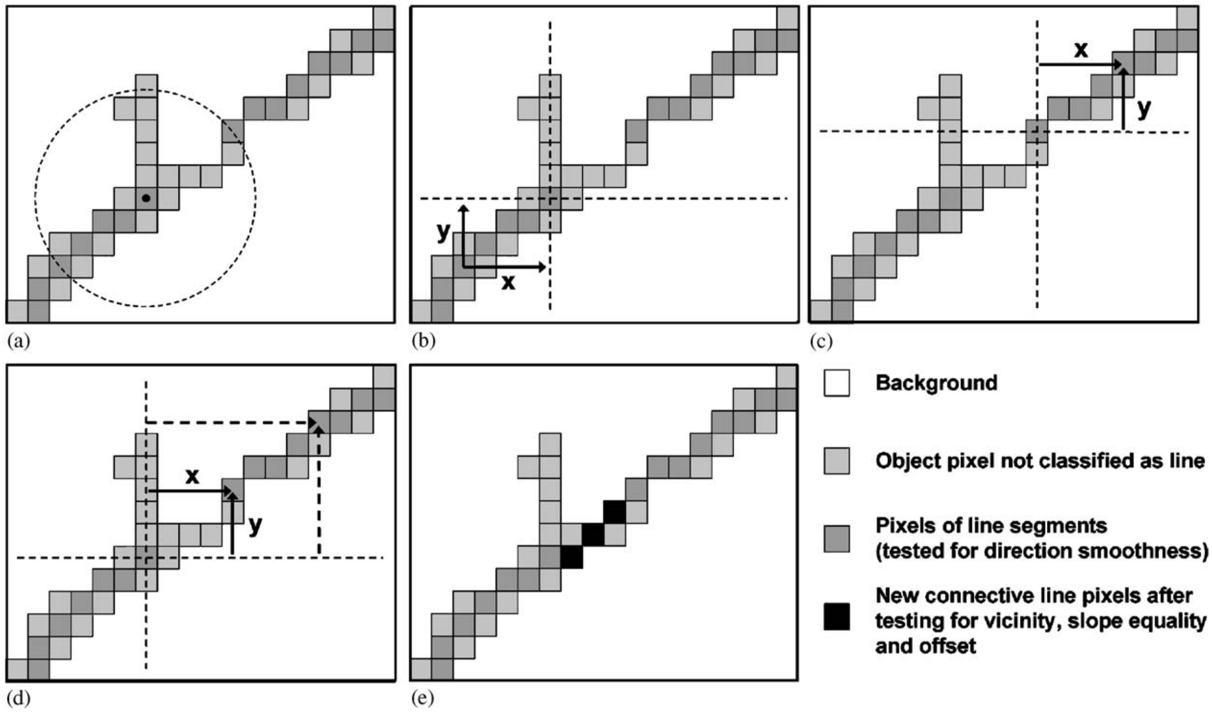

Fig. 6. Flow similarity testing. (a) Test for adjacency of two line ends. (b) Slope of line 1. (c) Testing for equality of slopes of line 1 and 2. (d) Parallel offset test. (e) Gap closing by minimum path distance.

Table 2
Pseudo-code for flow similarity testing of line segments

```
Search image I for end points of lines of category B
If there is a line end X of line L1
    Search the local neighborhood N of X
    If there is no other line end in N
        Mark X as "not connected"
    End if
    If there is a line end Y of line L2 within N
        Compute the slopes S1 of L1 and S2 of L2
        If S1 ≠ S2
            Mark X as "not connected"
        End if
        If S1 = S2
            Compute offset O between L1 and L2
            If O is not acceptable
                Mark X as "not connected"
            End if
            If O is acceptable
                Mark X and Y as "connected"
                Connect X and Y by minimum distance path
            End if
        End if
    End if
End if
```

connect two line segments:

- Within a pre-defined neighborhood of line end X of line one (category B) another line end Y of line two (category A or B) is found (Fig. 6a).
- The two line segments show slope equality. Slope of line one is simply computed as a direction measure between X and the fifth pixel of the same line (X_{-5}) defined by the horizontal and vertical distances between X_{-5} and the y- and x-axes, respectively, which cross X (Fig. 6b). These distances are projected in the opposite direction to Y. If a pixel of line two is found in the pre-defined direction and within the given distances or within the direct neighborhood of this point, the slopes of both lines are considered to be equal (Fig. 6c).
- The parallel offset between line one and line two has to be kept within an acceptable range. For this the above described opposite direction measure is projected to X. If a pixel of line two is found close to the pre-defined pixel, the offset is deemed acceptable (Fig. 6d).

The presented tests allow for deriving combined salient features to unambiguously detect lines and separating these lines from coalesced objects. If all three conditions are fulfilled the line segments are considered as parts of the same line and connected by minimum distance paths (Fig. 6e). Segments of category B, which could not be connected with another line segment, are converted to black. They could be part of a line but too short or too isolated. In such cases they remain in their original shape and can be classified later on based on geometric properties. They could also be coalesced with objects of a different category resulting in misclassifications.

Table 3
Features of prototypes and candidates of semantically relevant classes

	Object category	Features	Semantic meaning
Object prototypes	Forest symbol prototypes	$E=1$, size, $x/y \sim 1$, $R \sim 100$, C close to 1	Initial points for structural analysis of associated forest symbols
	Rocks and buildings	$A>400$, $E>10$, IDO$\geqslant 2$	Non-forest area objects
Object candidates	Short forest boundary segments	IDO<3, $A<400$, $E>3$	Delimiting forest area if touched
	Line dashes	$E=0$, x or $y \sim 10$	Forest area when crossing
	Line dots	$x/y \sim 1$, IDO$\geqslant 1$, x and $y \sim 6$	
	Forest symbol candidates	$A<50$, $x/y \sim 1$	Pre-classified forest symbol candidates
Remaining objects	One of the above classes coalesced with other objects	$A <$ threshold	Forest if embedded in forest area

$A=$ area, $R=$ area of surrounding rectangle, $E=$ number of holes, $C=$ circularity, $x=$ extent in x-direction, $y=$ extent in y-direction.

4.4. Structural analysis and semantic expansion

Next, the recognition of the single elements of forest and non-forest objects and the final extraction of forest cover by semantic expansion are described. In a first step, all pixels in the grayscale image, which belong to the black layer, are converted to black and connected components are computed, except for detected lines and text. These are transferred from the IDO image and marked. Thereby, coalesced forest symbols are frequently marked as parts of lines. The procedure consists of the following steps:

- *Level* I: Feature extraction from connected components and statistical classification based on distance functions to partition the n-dimensional feature space.
- *Level* II: Structural analysis based on relational features to iteratively classify forest symbol prototypes and candidates as associated forest symbols.
- *Level* III: Semantic expansion of forest cover based on the spatial arrangement of forest elements and semantically important non-forest objects.

4.4.1. Statistical classification (level I)

In Table 3 an overview is provided of features and their values, which carry saliency for different object categories or are used to determine candidates of objects categories. Rock, buildings and closed forest symbols (forest prototypes) are reliably classified as object prototypes, if not coalesced with other objects. Object candidates are found for forest symbols (not closed circular symbols), dashed and dotted line elements and short boundary line segments, which could not be identified by line detection (Table 3). These candidates are potential elements of compound objects. Thus they have to be further examined by structural analysis and semantic expansion, before they can be classified to one object category. Finally there is a number of remaining small pixel groups, which could not be classified consistently, such as parts of rotated characters.

4.4.2. Structural analysis (level II)

The classified forest symbol prototypes (Table 3), which could be classified by salient features, are the starting points for the structural analysis. The individual forest symbols are understood as “primitives”, whose spatial arrangement describes the synthesized “inner” forest area. Spatial and directional relations between these primitives (context) are described by rules or relational features. Based on these rules, each classified symbol is iteratively tested for association with other symbols before a membership to forest is definitely assigned to it (Fig. 7). The aim of this procedure is thus to classify the amount of *associated* forest symbols.

Basically, the detection of one forest symbol prototype (P) generates expectations about other forest symbols, prototypes or candidates, in its neighborhood. To ensure that P_1 is associated to a group of similar symbols the procedure, whose pseudo-code is presented in Table 4, tests first, whether there are a minimum number of prototypes P_i or candidates C_i within its local neighborhood (Fig. 7b). These symbols must not be separated from P_1 by a forest boundary. The size of the neighborhood is defined by the average Euclidean distance between forest symbols in the original map. If a sufficient number of P_i or C_i is found, P_1 is marked as “truly associated forest symbol” T_1 and each C_i in the neighborhood is converted to P_i (Fig. 7c). If not, P_1 is marked as “non-forest symbol” X_i. The new prototypes P_i are iteratively tested the same way, but now the neighborhoods are searched for C_i, P_i and T_i. The procedure runs iteratively until there is no more P_i found in the image (Fig. 7d–f).

The candidates of dotted and dashed line elements also have to be examined for association in order to reliably classify them. Here we used a procedure similar to the A* algorithm in Ref. [9] to track discontinuous chains of symbols. Only if there is a context to two other candidates in two opposite directions the considered candidate is marked as seed. Starting from these seeds, candidates found within the neighborhood are converted to a seed. The procedure runs until there are no more candidates converted to a seed.

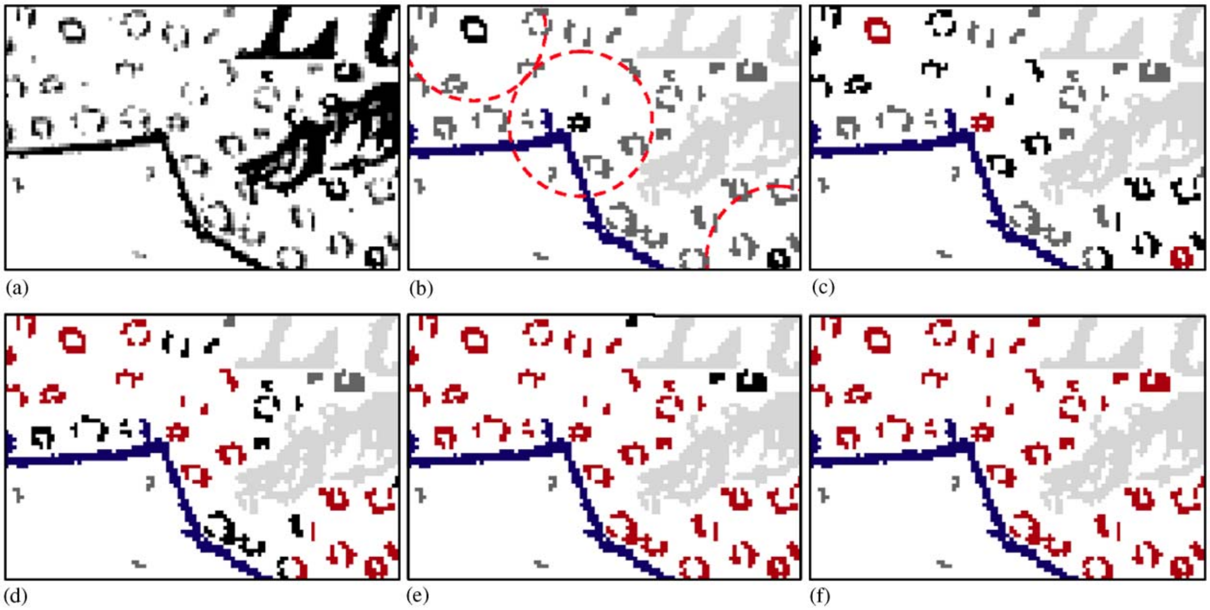

Fig. 7. Structural analysis of forest symbols. (a) Input image. (b) Candidates within the local neighborhoods (red dashed circles) of prototypes (black). (c) Associated forest symbols (red) and new prototypes (black). (d)–(f) Iterative analysis to find the set of forest symbols.

Table 4
Pseudo-code for structural analysis

```
While there are forest symbol prototypes P in image I left do
    Search I for P
    If one P is found
        Search the local neighborhood N of P for prototypes
        P′, candidates C′ and associated forest symbols T′
        If there are less than two P′, C′ or T′ counted in N
            Mark P as non-forest symbol X
        End if
        If there are at least two P′, C′ or T′ counted in N
            Mark P as truly associated forest symbol T
            Mark all candidates C′ in N as forest symbol prototypes P
        End if
    End if
End while
```

4.4.3. Semantic area expansion (level III)

The spatial arrangement of truly associated forest symbols T_i describes the inner forest area (Fig. 7f), which cannot be simply filled by forest cover pixel values. An appropriate forest extraction has to consider the semantic meanings of all relevant classified objects in the image. For this reason, semantic expansion is proposed to correctly expand the forest cover across the image space. Different objects trigger different actions when encountering forest area as follows (Fig. 8):

- Starting from pixels of any T_i, paths of pre-defined distances are followed in each direction.
- If a pixel of value T_i and no non-forest object is encountered along the path, the path pixels of background value are converted to forest. If no T_i is found nothing is done.
- If text is encountered from above or below, the path is extended in the same direction across the text. If text is encountered from left or right the path is extended upward and downward to test for embedding. If forest is found the path pixels are marked as forest (Fig. 8b).
- Rock is non-forest area, whose extent has to be defined spatially (Fig. 8a). If rock is touched all path pixels become forest values and the procedure terminates (Fig. 8b).
- The above steps are iteratively carried out to expand the inner forest area A (Fig. 8b).
- Pre-defined paths are followed then, starting at the edge of A to expand gaps between boundaries and A. If a line or a short boundary segment is encountered coalesced forest symbols are tested for embedding and the remaining gaps are expanded with forest values.
- The procedure runs until no more pixels could be converted to forest values.

As can be seen the procedure is based on object-specific semantic constraints. These constraints are linked to predefined actions when encountering objects of a certain map category. Single lined roads crossing forest area are automatically filled with forest pixels since they are considered as boundaries from two directions resulting in adjacent forest pixels. Dashed lines within forest area are intended to be converted to forest except where they are part of a double lined road.

5. Performance

In this section the results of the multi-step recognition process are presented and illustrated for four test images, shown in Figs. 9–12. In each of the figures the gray value image is shown on the upper left (a) where different critical

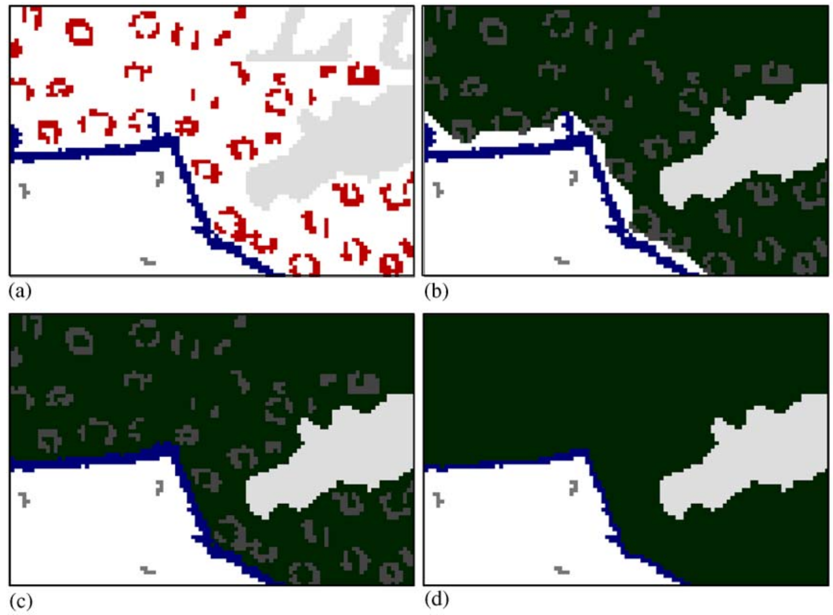

Fig. 8. Semantic forest cover expansion. (a) Associated forest symbols. (red), boundary lines (blue) and classified non-forest objects (gray). (b) Expanded “inner” forest area. (c) Expansion of remaining gaps between boundaries and “inner” forest area. (d) Final extraction and definition of the outer forest boundary.

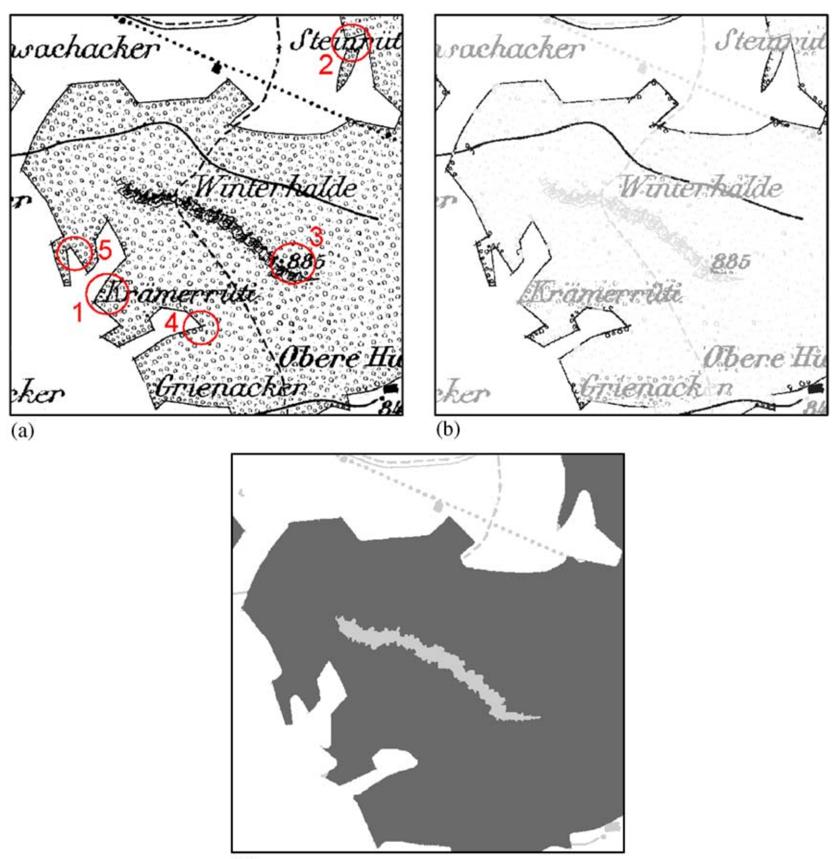

Fig. 9. (a) Test sample 1 with difficult spots circled in red. (b) Results of line detection (black), and character recognition (gray). (c) Results of final forest cover extraction.

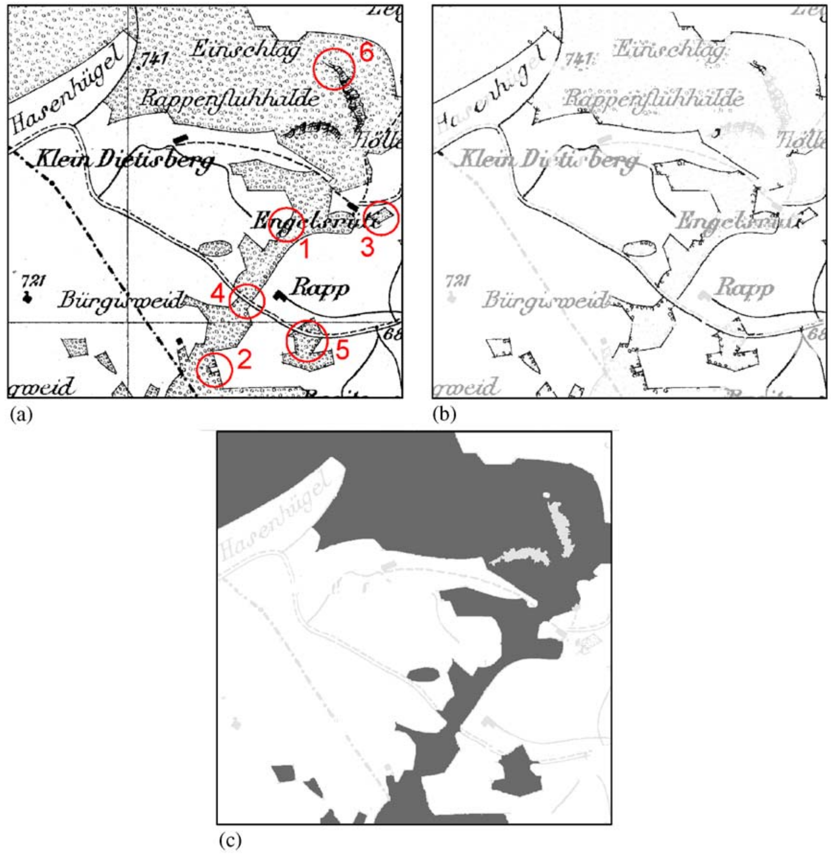

Fig. 10. (a) Test sample 2 with difficult spots circled in red. (b) Results of line detection (black), and character recognition (gray). (c) Results of final forest cover extraction.

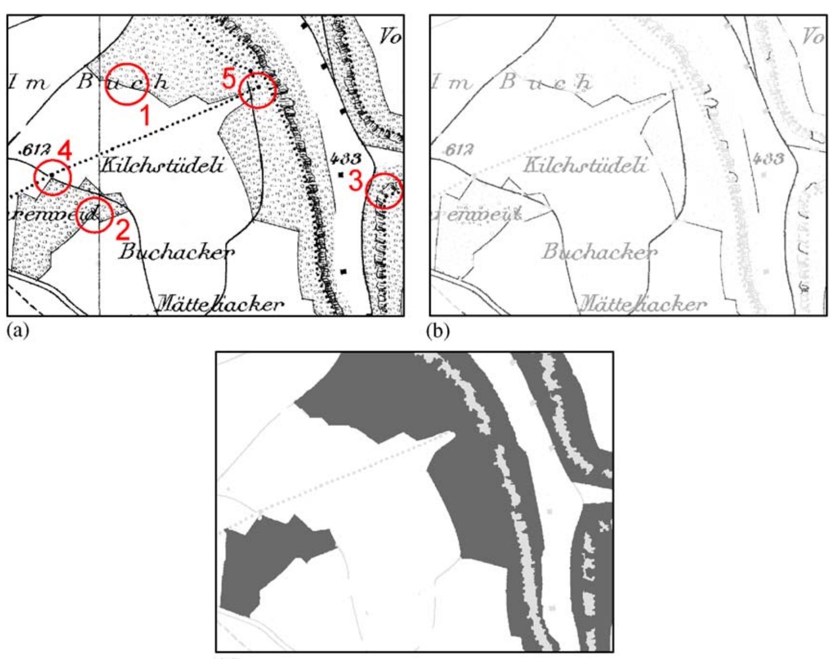

Fig. 11. (a) Test sample 3 with difficult spots circled in red. (b) Results of line detection (black), and character recognition (gray). (c) Results of final forest cover extraction.

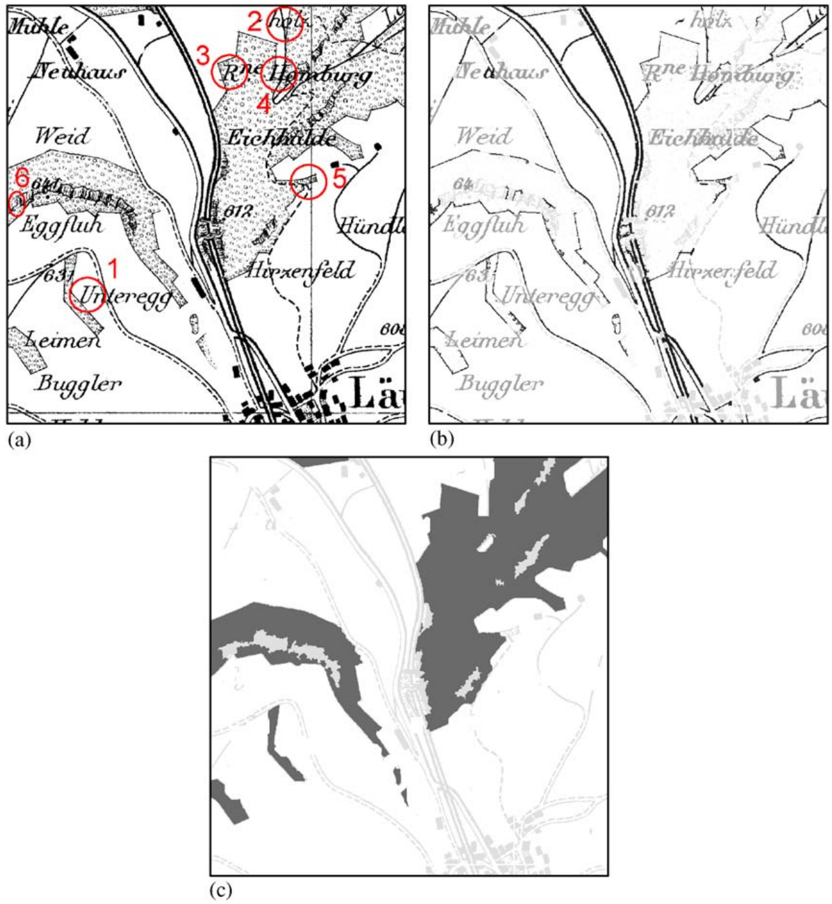

Fig. 12. (a) Test sample 4 with difficult spots circled in red. (b) Results of line detection (black), and character recognition (gray). (c) Results of final forest cover extraction.

aspects for recognition are circled in red. Reference to a circle in a certain image is given as "image(circle)", e.g. 9(4) for Fig. 9, circle 4. The results of character recognition (marked with dark gray) and line detection including the classified boundary segments (marked with black) are shown on the upper right (b). The final forest cover extraction after structural analysis and semantic expansion is shown on the lower image (c).

For evaluation purposes the results of the character recognition and the final extraction procedure were compared to reference data digitized by an experienced cartographic interpreter. Measures derived are *recall* and *precision* [32] for each step as well as confusion matrix-based global measures such as *percent correctly classified* (PCC) often referred to as *accuracy* [33], *Kappa coefficient of agreement* [34] and *normalized mutual information criterion* (NMI) [35] for forest cover extraction (Table 5). Units are words in shape prototype matching and single strings in character matching, both derived from two entire maps of 7000 × 4800 pixels each, and forest pixels in the final extraction, derived from the test images in Figs. 9–12. First, the performance and critical aspects of character recognition and line detection are commented on. Then their impact on final forest cover extraction is described.

5.1. Text recognition

The horizontal character recognition ensured the robust detection of at least one shape prototype in most text regions in the first stage indicated by $recall = 0.93$ (Table 5). Only few false registrations of prototype shapes were found ($precision = 0.97$). Character matching in the second stage showed a high recognition rate ($recall = 0.94$) but higher proportions of false registrations ($precision = 0.86$), which were mainly due to falsely recognized "1", "7" or "L" in lines because of low correlation thresholds similar to Ref. [18]. Some line segments were marked as characters if they are overlapped by text (e.g., Figs. 9(2), 10(1), 11(1), 12(1)–12(4)). Thus semantically important barriers such as road lines or forest boundaries were interrupted. But these errors were limited to the computed pre-selections, as described in the methods. As shown in Table 5 the recognition of characters of larger sizes performed almost perfect ($precision = 0.99$, $recall = 0.98$). This is related to their

Table 5
Results from single steps of multi-step pattern recognition

Step	Map category	Precision	Recall	PCC	Kappa	NMI	Units total
Horizontal text recognition (two-stage template matching)	Shape prototypes (smallest size, stage 1)	0.97	0.93	—	—	—	Text objects 1260
	All text strings (smallest size, stage 2)	0.86	0.94	—	—	—	Characters and numbers 7350
Horizontal text recognition (one stage)	Characters of larger sizes	0.99	0.98	—	—	—	Characters 328
Semantic expansion	Semantic expansion	0.97	0.95	0.97	0.94	0.81	Forest pixels 2,202,911

salient shapes, which were used for matching in only one stage.

5.2. Line detection

Line detection showed robust recognition results for well-defined lines but showed some limitations for the recognition of forest boundaries. If line sections are too short between two crossings or between a corner and the next crossing (e.g., Fig. 11(4)) the continuation criteria were not met and no line segments were detected. Occasionally the reason was the interruption of lines by text regions (e.g., Fig. 11(1)). Most of these short boundary segments were found in the classification. They can be recognized in Figs. 9b–12b by a higher density of coalesced forest symbols. There were some recognition errors due to falsely detected line segments in rock. This happened if rock is represented by smooth thin lines, which fulfill the conditions required for line tracking (e.g., Figs. 10(6), 11(3) and 12(6)). Altogether, most line segments, except some short strokes, could be identified and separated from other objects, which was the main objective of line detection. There are no accuracy measures given separately for line detection since its performance is directly reflected by the final forest cover extraction. A visual appraisal can be made from Figs. 9b–12b. As can be seen in Fig. 10b, the rotated place name was partially classified as line segments. If this word was located in forest area the short lines and the remaining pixel groups would be tested for embedding, occasionally resulting in minor errors, as described above.

5.3. Structural analysis and semantic expansion

The final extraction based on structural analysis and semantic expansion resulted in robust recognition results indicated by *precision* = 0.97 and *recall* = 0.95. Even more information about the accuracy is provided by PCC (0.97), Kappa (0.94) and NMI (0.81) (Table 5). This robustness is attributed to the almost perfect performance of the structural analysis. The expansion procedure strictly kept at the iteratively classified associated forest symbols. Thus the described problems in character recognition and line detection as well as some classification errors due to coalesced objects could be compensated in general or had only minor impacts on the final extraction. Some of these impacts are described in the following.

Forest boundary segments, which are overlapped by and thus marked as text regions, were not detected as termination criteria by the procedure. The reason is that forest was expanded across the text region only if forest values were found on the opposite side. This resulted in slight overestimations (e.g., Figs. 9(2), 11(2), 12(4)) or underestimations of forest area (e.g., Figs. 9(1), 10(1), 11(1), 12(1)–12(3)).

As described above, there were some misclassifications of *line-like segments within rock* e.g., at outer parts of the rock symbology (e.g., Fig. 10(6)) or anywhere if rock is entirely represented by thin line work or small isolated rock segments (e.g., Fig. 11(3)). This resulted in slight overestimations of forest area. Furthermore, in many cases the clear cut separation between rock and forest could not be made even visually due to coalescing or intruding forest symbols. These symbols were classified as part of the rock resulting in a negligible underestimation of forest.

If the *forest boundary* shows highly *acute angles* or two adjacent boundaries are assigned too close to each other, the expansion procedure slightly overestimated forest area by crossing this angle or gap outside the forest (e.g., Figs. 9(4), 9(5), 10(2), and 10(5)). The reason for this is that during closing the gaps between the inner forest area and boundaries the procedure did not stop after the first encountering of a forest boundary. It first examined coalesced forest symbols for embedding, which forbade the formulation of termination criteria. Thus the procedure occasionally crossed acute angles or close boundaries by the defined minimum search distance. Some instances were found where the outer forest limit was not reached due to acute angles inward causing premature termination of the expansion.

One typical but minor error is highlighted in Figs. 10(4) and 10(5) where a double lined road, consisting of a solid and a *dashed line*, crosses a forest patch. The elements of the dashed line are coalesced with other objects and could not be correctly classified. Consequently, forest area was expanded across the road. Furthermore, the pixels between the misclassified dashes, which intersect with the forest boundary, and the solid road line that acted as a barrier, were accidentally converted to forest area for a short distance outside the forest patch. For similar reasons expansion was occasionally terminated before reaching the misclassified dashes.

In most cases the remaining *short boundary segments* were successfully included into the procedure. Some small forest patches could not be identified since no forest symbol prototype could be detected as initial point for the structural analysis (e.g., Fig. 10(3)). In Fig. 12(5) the narrow parcel along the margin of a forest patch could not be detected since the expansion was interrupted by the misclassified elements of the dashed line. Altogether, the forest cover extraction showed significant robustness (Table 5). Errors in character recognition and line detection were compensated by structural analysis and semantic expansion.

6. Conclusions

In this paper a multi-step recognition process for the extraction of compound forest cover information from historical topographic maps is presented. This process overcomes the inherent complexity and low graphical quality of the hand-drawn map. The concept of saliency has been introduced to design a systematic strategy for the stepwise detection of the information of interest. Based on salient features map categories to be recognized in each step and appropriate methods are determined.

Consequently text recognition by two-stage template matching and line detection based on sequential line tracking and flow similarity are the first two steps in which salient features are used for detection of objects that interfere the direct recognition of forest. Salient features of text were found in typical shape prototypes occurring in characters. Lines are found by combined salient features for smoothness and directional similarity of pixel chains representing the medial axis of objects. To determine the medial axis the inner dimension of objects (IDO) is proven to be useful.

Based on connected components statistical classification is applied to find forest symbol prototypes and candidates of all relevant forest and non-forest objects. Hierarchical structural pattern analysis is applied then, to iteratively test forest symbol prototypes and candidates for association with similar objects and to classify them as associated forest symbols. Finally, semantic expansion determines the forest area, which is defined by the spatial arrangements of associated forest symbols, forest boundaries and semantically relevant non-forest objects. Class-specific semantic constraints trigger pre-defined actions, such as termination or inclusion, to expand and extract forest area. The result is a robust procedure for the recognition of low quality compound map graphics. Since the extraction strictly keeps at the arrangement of iteratively recognized forest elements, minor recognition errors in the two first steps can be compensated. The concept of saliency proved to be very useful for designing a systematic and targeted process to overcome the complexity of such recognition tasks when a particular pattern is of interest.

The proposed process has been tested on a group of 1:25,000 maps dating from the years 1872 to 1876. It could be observed that maps published 10 or 20 years later show new variations in text due to different stencils used. Thus to overcome these variations scale-invariant template matching would have to be tested. Basically, our process is dependent on a minimum quality level of the text and graphic representations but also on the quality of color segmentation in the pre-processing stage. For recognition tasks, which also aim at the automatic detection of colored objects such as historical hydrography, wetlands or elevation contours, more sophisticated approaches of color image segmentation [36] have to be developed. For this reason the authors will pursue research in this direction. The approach will be based on seed definition in color space, fuzzy homogeneity measures [37] and region growing. Thus attributes from color space and geometric constraints [5] as well as spatial relations between objects will be used to extract the color layers. The aim will be to overcome color variations between different maps, noise, mixing colors and false coloring, and to maintain topological relations.

7. Summary

This paper presents a method for the extraction of high-level compound forest cover information from manually produced scanned historical topographic maps. The contained forest cover is a unique data source for GIS-based land cover change modeling. As a case study, this work focuses on the so-called Siegfried Map, the Swiss national topographic map series of the 19th century. The map is of low graphical quality which is related to closely spaced map symbols, overlapping/intersecting hand-drawn graphics and text as well as ill-defined transitions to background through blurring. Forest cover is represented by irregularly distributed forest symbols and boundary lines.

To conceptually order the extraction process, which is achieved by multi-step recognition, the concept of saliency is introduced. Saliency is defined as the existence of non-ambiguous color or shape features attributed to each object of one particular map category which do not occur in all other categories. By finding salient features in the image the choice of the adequate next step is facilitated by first deselecting non-forest objects which impede forest recognition. After forest cover elements are sufficiently isolated salient features can be determined for robust extraction of forest cover.

The first recognition steps to be carried out for deselecting non-forest objects are character recognition by two-stage template matching and line detection by sequential line tracking based on the inner dimension of objects (IDO). For these two steps salient shape prototypes of text and combined characteristics of the medial axis of line segments are used as salient features, respectively. A method for structural analysis is developed for hierarchical classification of forest symbols based on their spatial context to examine whether they are associated with a larger amount of surrounding similar objects. Semantic processing is used for the final extraction of the forest area. Based on the recognized structures and classes, which are semantically relevant, forest cover is expanded under pre-defined rules and actions. These actions such as termination or filling are thus triggered by different meanings of objects encountered during expansion.

The result is a prototype for robust extraction of forest cover which is defined by the spatial arrangement of the individual forest symbols and forest boundary lines. The multi-step recognition process has been tested on a group of maps in the scale of 1:25,000. It showed an accuracy of Kappa $= 94\%$ when comparing the automated extraction with the result of a visual inspection despite some initial recognition errors in character recognition and line detection. Thus the extraction procedure accepted minor errors in the first two steps and showed a high robustness in the final recognition of the forest cover compounds. The reason is that structural analysis resulted in almost perfect classification of the associated forest symbols and semantic expansion strictly kept to the local environments of these symbols.

Consequently, a potential for automatic extraction of forest cover from larger regions could be identified. In the near future the approach will be further tested to include new variations in map graphics which occur on different map pages.

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Paper II

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Research Article

A Conceptual Framework for Uncertainty Investigation in Map-based Land Cover Change Modelling

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Abstract
Uncertainty research represents a research stream of high interest within the community of geographical information science. Its elements, terminology and typology are still under strong discussion and adopted methods for analysis are currently under intensive development. This paper presents a conceptual framework for systematic investigation of uncertainty which occurs in applications of land cover change modelling in Geographical Information Systems (GIS) based on historical map data. Historical, in this context, means the map is old enough to allow identification of changes in landscape elements of interest, such as vegetation. To date such analyses are rarely conducted or not satisfactorily carried out, despite the fact that historical map data represent a potentially rich information source. The general validity and practicability of the framework for related applications is demonstrated with reference to one example in which forest cover change in Switzerland is investigated. The conceptual model consists of three domains in which main potential sources of uncertainty are systematically exposed. Existing links between data quality research and uncertainty are investigated to access the complex nature of uncertainty and to characterise the most suitable concepts for analysis. In accordance with these concepts appropriate methods and procedures are suggested to assess uncertainty in each domain. One domain is the production-oriented amount of uncertainty which is inherent in the historical map. Vagueness and ambiguity represent suitable concepts for analysis. Transformation-oriented uncertainty as the second domain occurs owing to editing and processing of digital data. Thereby, the suitable concept of uncertainty

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is error. The third domain is the application-oriented uncertainty which occurs in comparing semantically different data. This domain relates to multi-temporal discord which assumes the assessment of 'equi-temporal' ambiguity and is thus connected to the production-oriented domain. The framework provides an estimation of the overall amount of uncertainty. This can be linked to subsequent assessment of 'fitness for use'. Thus the model provides a practicable and systematic approach to access the complex nature of uncertainty in the scope of land cover change modelling.

1 Introduction

Historical maps contain interesting information for deriving knowledge about the historical landscape and changes in land use or land cover over time. Historical maps in this context are defined as maps representing the past landscape back for periods which are of reasonable length for the intended application. In using them for target applications such as land cover change modelling, these periods have to be at least 10 years. Any map and geographical database represents entities of the real world as generalized, incomplete and abstracted phenomena resulting in simplified descriptions (Veregin and Hargitai 1995). Consequently, uncertainties in historical maps occur to a rather high degree as described by Plewe (2002). The level of such indeterminacies (Williamson 1994) which is contained in the map thus depends on the methods of data collection and instructions used. In this context, the application of inconsistent methods, different and vague definitions, subjectivity due to interpretation and lack of reference and evidence information cause uncertainties, respectively.

Additional aspects of uncertainty have to be considered due to the procedures of data handling such as editing and transformation, and the subsequent application. Consequently, the nature of uncertainty occurring in using historical geographic data is extremely complex, especially if natural phenomena are considered. Digital cartography has entered a new dimension since the development of Geographical Information Systems (GIS) in the 1960s. There is plenty of digital spatial information with varying accuracy produced for different purposes. Nowadays, increasing capabilities in geo-processing and a growing number of application fields for GIS enable the user to incorporate such data from different sources into complex GIS operations. The thread of misleading results and wrong spatial decisions which grows with this development has led to increasing research in the fields of spatial data quality and uncertainty in recent years (Guptill and Morrison 1995, Burrough and Frank 1996, Lowell and Jaton 1999, Hunsaker et al. 2001, Foody and Atkinson 2002, Shi et al. 2002, Zhang and Goodchild 2002, Shi et al. 2003).

The discourse of spatial data quality as the totality of characteristics of a product that fulfils both the stated and implied needs of a user (ISO 8402) has occupied much research. The objective of reporting spatial data quality is the assessment of the fitness of the data for the intended use (Chrisman 1984, Aalders 2002). Therefore, consistent standards and definitions for data quality elements are required to realise systematic approaches (Veregin and Hargitai 1995). The Spatial Data Transfer Standard (SDTS 1992) is one important standard of spatial data quality in which several components are identified. The commission of the International Cartographic Association (ICA 1996) suggested the consideration of additional elements (Guptill and Morrison 1995). Further standards such as defined by the Comité Européen de Normalisation (CEN 1997) or the

International Organization of Standardization (ISO 2001) are more related to the transfer of data quality information between users.

In many cases true values of objects in the real world represented in geographical data are not obtainable such as for natural phenomena or other indeterminate objects. The user is always left uncertain about the truth to a certain degree. Terms like error, inaccuracy and imprecision assume that the truth can be reached. Uncertainty, as doubt about the information which is recorded at a location (Fisher 2003), represents a more appropriate perception. Zhang and Goodchild (2002) defined uncertainty as a measure of the difference between the data and the meaning attached to the data by the current user. Thus it can be seen as a result of error, ambiguity, vagueness or lack of information (Fisher 1999, Atkinson and Foody 2002) and forms an umbrella term for these concepts. There are other definitions of uncertainty in the literature (e.g. Bennett 2001, Elith et al. 2002 or Ahlqvist et al. 2003) which describe slightly different views but have similar meanings.

The objective of both concepts, reporting standards of spatial data quality and investigation of uncertainty is to enable the user to assess 'fitness for use'. Fisher (2003) recently argued that there is a discrepancy between these approaches. They follow completely different tracks although they should be seen as complementary. It is obvious that elements of spatial data quality cannot predict all aspects of uncertainty such as vagueness (Fisher 2003). Furthermore, there is a traditional relationship of spatial data quality to the production and transfer of cartographic information and not to its use (Veregin 1999, Fisher 1999, 2003). Since aspects of use have been recognized to be an important source of uncertainty (Beard 1989, Gottsegen et al. 1999) it is essential to include this aspect in quality assessments. Research on spatial data quality thus requires further advances to reach this objective of assessing fitness for use (Veregin 1999). However, elements of spatial data quality provide valuable knowledge to evaluate geographical information. In deriving different forms of uncertainty (Agumya and Hunter 1997) from data quality aspects the investigation of existing indeterminacies is thus supported.

As the introduction above suggests, change detection studies based on historical maps involve a great deal of complexity and many forms of uncertainty. Due to this complexity, conducted evaluation processes often suffer from incompleteness and lead to doubtful results of subsequent applications. Evidently, there is a lack of systematic approaches in assessing the complete amount of uncertainty which occurs in conducting target applications such as landscape change modelling based on historical maps. Discussion is still going on and theoretical background to different concepts of uncertainty in geographical information is not yet well established. Furthermore, many terms, definitions and models regarding data quality and uncertainty lead to some confusion.

This paper presents a conceptual framework for systematic and objective analysis of uncertainty which occurs in the scope of land cover change modelling based on historical maps. The framework considers different components of uncertainty, called domains, which are derived from single components of a GIS. These are data acquisition, data handling and the use of the data (Longley et al. 2002). Within these domains potential sources of uncertainty are exposed and occurring types of uncertainty are discovered. In accordance to these types or concepts suitable techniques for analysis are suggested. Such a framework allows the user to reach an objective decision about whether the data are fit for the intended use based on the occurring uncertainty in each domain. It provides the needed basis for an evaluation of the results of the subsequent application. The general validity of the framework to related cases of using historical map information for land cover or land use change modelling is stated. A case study in Switzerland is described as an example, in which maps from the nineteenth century are used to objectively analyse the change of forest cover to date.

Since uncertainty has to be understood in its entire complexity for comprehensive investigation, different concepts are explained in a theoretical section. This procedure is an attempt at contributing to decrease confusion over terms and definitions and to strengthen the theoretical background.

2 Coming to Terms with Uncertainty Terminology for GIS

One common though not very comprehensive approach to characterise uncertainty in geographical data is the determination of different forms or dimensions such as attribute, positional and temporal uncertainty. These forms are closely related to and can be derived from data quality elements. This implies a close relation to the production and transformation of spatial data, accordingly. As a consequence not all aspects of uncertainty can be described satisfactorily. For a complete understanding of its complex nature and to formulate appropriate assessment methods more intuitive concepts and their links to quality aspects have to be found.

In this paper, uncertainty in GIS is defined as the lack of knowledge about: (1) objects of the real world due to erroneous measurement, vague definitions and concepts or unknown and ambiguous meaning; (2) effects of transformations performed on the data; and (3) the latter's suitability for the intended application.

Different types or conceptualisations of uncertainty, which are included in this formulation, can be identified by considering the 'problem of definition' of classes of objects or individual objects (Fisher 1999). They provide the needed intuitive view to the nature of indeterminacies in geographical information and embrace human cognition of the real world. Based on recent suggestions by Fisher (1999), Klir and Wierman (1999) and Zhang and Goodchild (2002) they are classified into error, vagueness and ambiguity (Figure 1). Ambiguity occurs in two different aspects: discord due to classification systems and non-specificity of definition.

To avoid confusion these terms will be defined briefly:

Error, which includes inaccuracy in cases of systematic error and imprecision in cases of random errors, is the difference between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition (Oxford Reference Online 1996). Thus, in considering GIS, the knowledge of the true value in the spatial, attribute and temporal dimension is assumed and error can be measured as the resulting deviation. In some cases error is understood as being synonymous with uncertainty (de Bruin and Bregt 2001, Crosetto and Tarantola 2001, Elith et al. 2002), in others it is considered separate from it, as from a science of measuring point of view. But, as proposed recently by some authors within the GIScience community (e.g. Fisher 1999, Zhang and Goodchild 2002), error is considered as one conceptualisation of uncertainty to describe the case of measurable deviation from the true state where no problems of definition occur.

Vagueness can be defined as indeterminacy due to a lack of distinctness between ill-defined or fuzzy classes of objects or individual objects. In GIS vagueness in definition causes doubt over the membership of a considered location to one class or several classes.

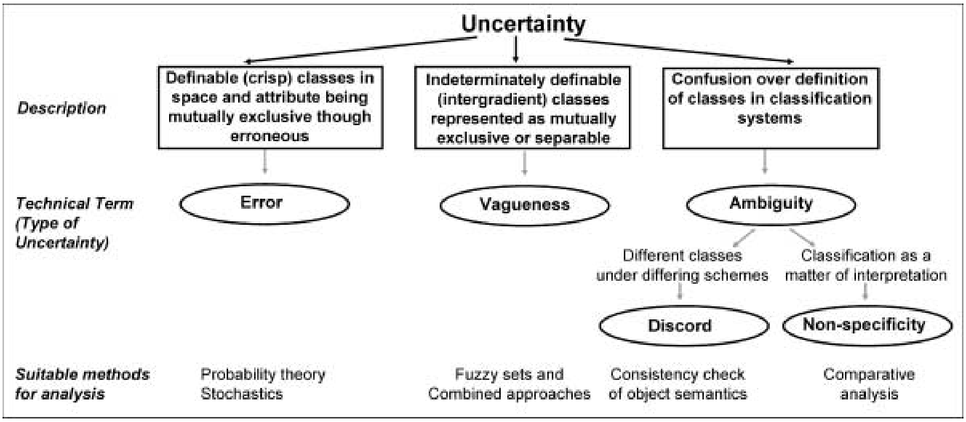

Figure 1 Classification scheme of types of uncertainty (based on Fisher 1999 and Klir and Wierman 1999)

Issues for semantic treatment often include the way to resolve the Sorites paradox (Williamson 1994) leading to the consideration of degrees of truth. There is a discrepancy among philosophers and geographers, whether to perceive vagueness as a property of objects (Tye 1994), as purely linguistic (Bennett 2001), epistemic in nature (Williamson 1994) or as purely semantic (Varzi 2001, Kulik 2001). This paper follows the latter case, as will be described below.

Ambiguity is the confusion among concepts which have the same name, but more than one definition (Fisher 2000). Such concepts have more than one meaning attached for classification. Thereby, discord defined as the lack of agreement occurs if one object is clearly defined but is shown to be a member of different classes under differing classification schemes or interpretations. Non-specificity (similar to what Bennett (2001) understands as "conceptual vagueness") describes the occurrence of ambiguity if the assignment of an object to a class is unsettled at all. It is then a matter of interpretation and prone to subjectivity.

To improve our understanding of the nature of these different (but not exclusive) concepts of uncertainty, existing links to 'tiers' of ontology in GIS (Frank 2001) (ontology: the study of the nature of being, of what exists or what can be known) are of great use. Below the occurrence of uncertainty in these tiers – for the case of collecting spatial data for map production – is described briefly.

Starting from the bottom, cognitive agents or surveyors and creators have subjective knowledge about the real world (tier 4) which is incomplete. It is used to deduce facts and to make decisions. Depending on the degree of restriction social ontology (tier 3) limits the scope of subjective decision, e.g. through defining landscape elements by an agency. Both approaches together allow for the derivation of semantic terms characterising features in the real world. If objects are not clearly and semantically defined, non-specificity due to subjectivity is introduced. Existing inconsistency of social and subjective aspects (Frank 2001) causes discord if objects belong to different classes under the different classification schemes applied. In this context, ambiguity occurs prior to any further process of observation or spatial representation. If such ambiguous data are incorporated into the spatial dimension they cause typically severe spatial effects.

In the observation of the physical world (tier 1) and the determination of objects (tier 2) cognitive elements play a considerable role. Recognition of things by comparing them to known objects, determination of their locations by perception within the environment and detection of changes and processes over time represent three cognitive subsystems within the mind of the surveyor. Types of objects are described by schema, which are used to identify objects by sensory observation through abstraction (Mennis et al. 2000). This categorisation aims at the representation of conceptual entities which describe the human-independent reality (tier 0).

During these processes the surveyor uses the semantic definition of the considered object (from tiers 3 and 4) as schema to identify objects. If one location cannot be classified in the sense of belonging to one class of objects or another but shows partial membership to several classes the definition is found to be vague. Thus vagueness arises due to overlapping definitions, which do not allow clear distinction of objects. Consequently, this paper holds with the perspective described by Varzi (2001), that vagueness has to be considered semantic. It becomes obvious in relation to the spatial context of the considered object to other objects or classes of objects. This is typical for natural objects which are often ill-defined and fuzzy bounded but still represented as well-defined homogeneous entities. Couclelis (1996) combined different kinds of empirical characteristics, observation mode and user purpose to distinguish different cases of geographical entities with ill-defined boundaries.

If the definition can be supposed to be precise and distinctive and objects are conceptualised as entities with sharp boundaries, the occurring deviation is prone to error. In these cases it can be assumed that the spatial deviation is due to erroneous measurement of phenomena in the real world. It is then understood as being probabilistic in nature.

There is a distinction between error, vagueness and ambiguity. Error is not due to problems of definition. Vagueness arises due to overlapping definitions and is thus only considerable in the context of an environment with other objects or classes of objects. Ambiguity is caused by definitions with different meaning under varying classification schemes (discord) or weak definitions (non-specificity) without consideration of its environment. Thus, it is proposed to represent ambiguity separately from error and vagueness (Figure 1).

3 Historical Data Sources

3.1 Historical Topographic Map

In the year 1868 the Swiss Federal Bureau of Topography initiated the field survey for a new national topographic map. The so-called 'Siegfried' map was published at scales of 1:25,000 for the midland regions and 1:50,000 for the mountain regions. Practically, the original field documents of the 'Dufour' map (the preceding national topographic map at a scale of 1:100,000) were revised or resurveyed to produce a new map. The map was characterised by higher spatial resolution and represented in the old Berne coordinate system.

During the field survey one of the classical topographic methods, the 'Messtischverfahren' (plane-table method) was applied. The higher resolution and details of the map contents such as rock signatures put Swiss topography into a leading position in European cartography. Growing public interest in more detailed maps from science, the tourism sector and the military could be satisfied, and indeed were until the 1930s.

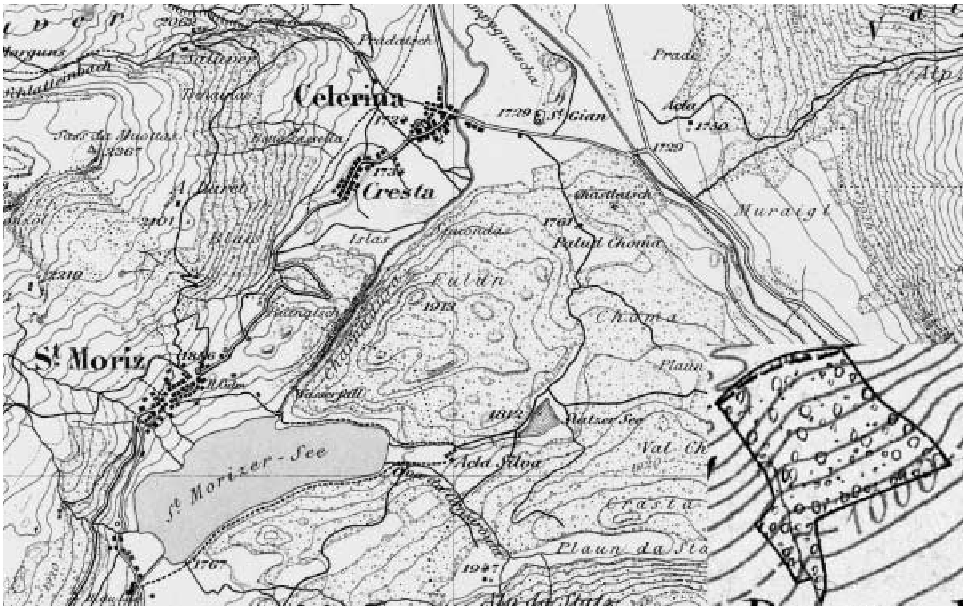

Figure 2 The Siegfried map: page 518 in the scale 1:50,000, published in 1874; bottom right: detailed representation of forest cover in the Siegfried map

The interesting point for this study is the integration of forest cover into the field survey. Its symbolic representation was prescribed by instruction as small black circles and dots. They were irregularly distributed over space (Figure 2). The forest boundary was drawn as a thin black line. In cases of open stands no boundary appeared (Siegfried 1871). The reproduction methods were still accomplished manually (copper engraving and lithography). Thus the map graphics in the final product are represented as extremely heterogeneous and variable drawings in shape and size. Information about applied methods, mapping rules and used definitions are hardly accessible. Compared to modern practices of map production and survey the accuracy of the representation is supposed to be much lower. However, the mapping of forest cover over the entire area of Switzerland in the nineteenth century provides a unique opportunity to evaluate its past distribution and to quantify forest cover change over time scales of more than 100 years in unprecedented detail.

3.2 Reference Data

For uncertainty analysis, some reference information of higher accuracy and if possible from the same point in time has to be found (Zhang and Goodchild 2002). Such sources must cover a minimum representative area.

Community plans at a scale of 1:5,000 or 1:10,000, which preceded cadastral mapping in Switzerland, already existed at this time and contained forest cover. Consequently, these maps can be supposed to be closer to the true state of reality.

The instructions for data survey are much more detailed which allows the investigation of the meaning of the objects. It is important to bear in mind that these reference sources are also maps and thus suffer from abstraction and generalisation to a certain

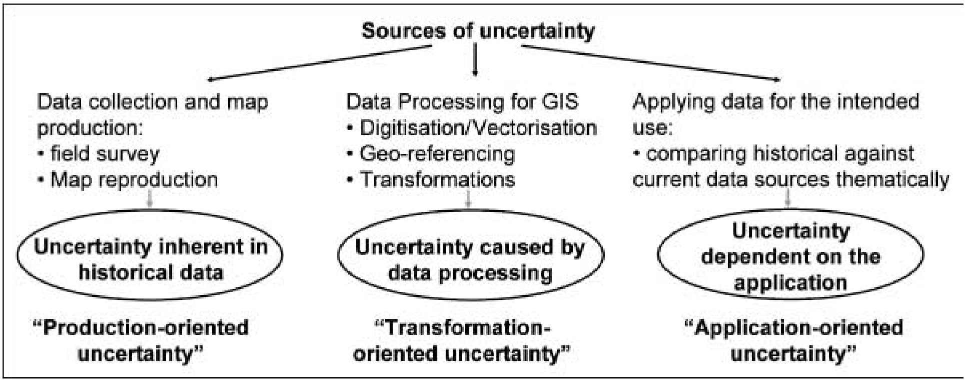

Figure 3 Conceptual framework for complete uncertainty investigation in using historical map information for subsequent land cover change modelling

degree. Furthermore, the attribute meaning of forest might not be the same in both maps. It has to be investigated as far as possible.

4 A Conceptual Framework For Uncertainty Investigation

Uncertainty in geographical data arises from various sources and is thus complex in nature. This complexity increases if further sources due to data handling and the subsequent application are considered. Furthermore, concepts to characterise occurring uncertainty are often not used in a comprehensive manner to be applied to practical problems. Thus the investigation of uncertainty often suffers from incompleteness and a lack of systematic approaches for analytical treatment. Therefore, systematic identification of the main sources of uncertainty within the components for construction of a GIS is suggested. These are: data acquisition, data handling and geographic tools and use of the data (Longley et al. 2002) (Figure 3). Accordingly, uncertainty is classified into three domains:

- **Production-oriented uncertainty:** The amount of uncertainty inherent in the historical map (related to source error; Goodchild 1991).
- **Transformation-oriented uncertainty:** The amount of uncertainty caused by data processing and editing (related to processing error; Goodchild 1991).
- **Application-oriented uncertainty:** The amount of uncertainty dependent on the intended application (related to use error; Beard 1989).

This classification represents a suitable basis for comprehensive and complete investigation of uncertainty in its entire complexity. Each of the above classes can be understood as one domain of a conceptual uncertainty model. This paper describes the derivation of suitable concepts of uncertainty and their implied analytical techniques within each of these domains.

4.1 Production-oriented Uncertainty

4.1.1 General Aspects of Production-oriented Uncertainty

Natural objects are characterised by vague definitions, spatial variance and heterogeneity, inherently fuzzy boundaries and transition zones (Burrough 1996). They are often

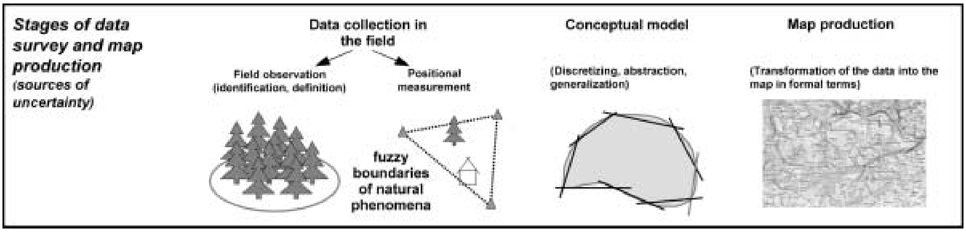

Figure 4 Stages of data survey and map production as sources of production-oriented uncertainty

represented in maps as sharp bounded or crisp, homogeneous entities (Figure 2). This has been a common practice in traditional cartography. In other words, the perception of phenomena of the real world (Couclelis 1996) has been simplified and generalised during cognitive processes. Accordingly, objects have been classified in the sense of belonging to one class or another (Fisher 1999) and uncertainty is expected to a high degree.

The single stages of data collection and map production carried out a long time ago have to be understood as sources of uncertainty which are inherent in the map. These uncertainties can be characterised in relation to ontology elements (section 2). Thus it can be seen as the production-oriented amount (Figure 3) which summarises 'inherent' uncertainty and 'assertion' uncertainty described by Plewe (2002). These stages (Figure 4) include: data collection (implying field observation and measurement), and transformation of the collected data into the final map. The latter implies the imposition of a conceptual model for real phenomena which are mapped through the use of graphical symbols. This results in generalised and abstracted data represented in the map (Burrough 1996). Thus uncertainty depends on the conceptualisation process, the accuracy of practical fieldwork and cartographic reproduction methods as well as on the detail of instructions for data collection and mapping. The reason for considering uncertainty due to conceptualisation (inherent) and due to measurement (asserted) (Plewe 2002) as one domain lies in the lack of distinction between both processes. Since ill-defined natural phenomena (motivated entities in Plewe 2002) are considered, which are identified by subjective interpretation and suffer from the lack of reference information, it is impossible to make this distinction.

Elements of spatial data quality (ICA 1996) are considered production-oriented and represent commonly recognised aspects to derive useful knowledge about the database. Consequently, forms of uncertainty which are derived from single data quality elements describe the resulting effect due to the lack in quality. This quality-related view is used below to find a systematic way of assessing uncertainty, in exploring existing links to uncertainty concepts which are defined in section 2. As will be shown, such links are not straightforward, possibly suggestive and yet not well researched (Fisher 2003). There are usually manifold interrelationships in the way that a lack of quality can cause different types of uncertainty and vice versa.

Positional uncertainty (the deviation of a considered element from reality in position, relative to some type of geo-reference, shape (geometry) and topology (Aalders 1997) can be introduced at every single step of the positional information production line (Drummond 1995), starting with field measurements and ending with map creation. Attribute uncertainty (the difference between a given attribute and some reference of higher accuracy; Goodchild 1995) and positional uncertainty often have to be considered as inseparable and interrelated (Goodchild 1995, Molenaar 1997). Thus the spatial effect due to indeterminate and vague definitions used for the identification of natural objects and their ill-defined boundaries often overlaps aspects of pure positional uncertainty. This relates predominantly to the concept of vagueness (Figure 8). If attributes are well-defined and the boundaries are crisp, the observed deviation is prone to error.

Consistency (a measure of the internal validity of a database; Veregin and Hargitai 1995) relates to production-oriented discord (Figure 8) which thus can be seen as 'equi-temporal'. For investigation purposes, it has to be determined whether the map created by different topographers or map makers resulted in consistent data in relation to semantics for different objects and uniformity of methods and their accuracy.

To estimate how faithfully the map represents the real world, or in this case the semantic model from the reference data source, completeness (Brassel et al. 1995) can be investigated. Generalisation, implying elimination, merging or aggregation of features in relation to resolution and abstraction causes incompleteness to a certain degree (Veregin and Hargitai 1995). This aspect represents an important component for the derivation of a semantic model. It provides mapping rules such as the minimum size of mapped landscape elements.

For confident assertions it is important to estimate temporal uncertainty (Guptill 1995) or currency through approving the timeliness of reference data in relation to the map of investigation. Therefore, the temporal gap between survey time and publication time of that map also has to be investigated. The derivation of a semantic model from the reference map refers to the meanings of geographical objects and implies different concepts, such as completeness, consistency, currency and attribute uncertainty. Semantic uncertainty (Salgé 1995) describes the semantic distance between geographical objects and the perceived reality or in this case the semantic reference model. Thus, it relates to the concept of non-specificity. Lineage represents a useful descriptive feature for describing the life cycle of the data and improving the understanding of the single stages of map production, such as survey, registration in a field book and final map reproduction.

Due to interrelations and overlapping effects between different forms of uncertainty in cases of natural phenomena a cumulative spatial effect of uncertainty arises. As shown, the most suitable concepts for investigation are vagueness and ambiguity. At first, a semantic model as derived from the reference information (in evaluating social reality and subjective knowledge) is needed to estimate non-specificity. This is accomplished by comparative analysis and interpretation (Figure 1). Discord relates to the consistency of this model and further accuracy measures over the entire data source (such as map pages). Frank (2001) describes consistency constraints in relation to ontology in GIS. Due to non-distinctness of abstracted object classes as a result of vague definitions a spatial effect of inherent uncertainty is expected. The most suitable concept to address this spatial effect in the historical map is the concept of vagueness (Figure 8).

4.1.2 Assessment of Spatial Effects due to Production-oriented Uncertainty

The assessment of the spatial effect of production-oriented uncertainty refers to the comparison of the historical data with reference data sources of higher accuracy from the same point in time. Thus it implies the investigation of the agreement between representations of both data sources. The assessment of non-specificity is a pre-condition for objective evaluation of this spatial effect. It will be described in section 4.3 in relation to the subsequent application.

The integration of uncertainty into spatial data corresponds to the process of general spatial data modelling (Gottsegen et al. 1999). Thereby, the conceptual data model (representation of data as fields or objects) is of major interest. As noted before, one special characteristic of historical maps is that the process of conceptual data modelling has already been formally accomplished to a certain degree. Thus the analysis has to deal with already generalized and abstracted data and predefined crisp boundary representations even for natural phenomena. Since this is in contradiction to the perception of them, uncertainty aspects have to be incorporated into these given data models, accordingly. In practice, each location of natural phenomena has to be treated as fuzzy or indeterminate to some degree to meet the concept of vagueness.

There are several requirements of fundamental importance for a data model with uncertainty referring to categorical maps (Goodchild 2003). Some of them are: addressing of variable confusion at every point between true classes and reference classes, consideration of spatial auto-correlation and of effects from generalisation as well as invariance of model realisations if underlying representations change. They are not further discussed in this paper. The following techniques have been applied to different application fields such as remote sensing, predictive habitat modelling in ecology or geographical analysis. They will be described, briefly, in order of increasing complexity and level of sophistication for the given problem.

The assessment of *classification uncertainty* represents one of the most prominent techniques in the context of map comparisons. The accuracy of recorded classes in the map is assessed by comparing them against the corresponding reference classes (Figure 5). Simply spoken, uncertainty occurs when the wrong class is assigned to a given unit (Goodchild 1995). Several measures can be derived from a confusion matrix, such as User's accuracy, Producer's accuracy, per cent correctly classified (PCC) or the Kappa coefficient of agreement according to the specified sampling units and the sampling

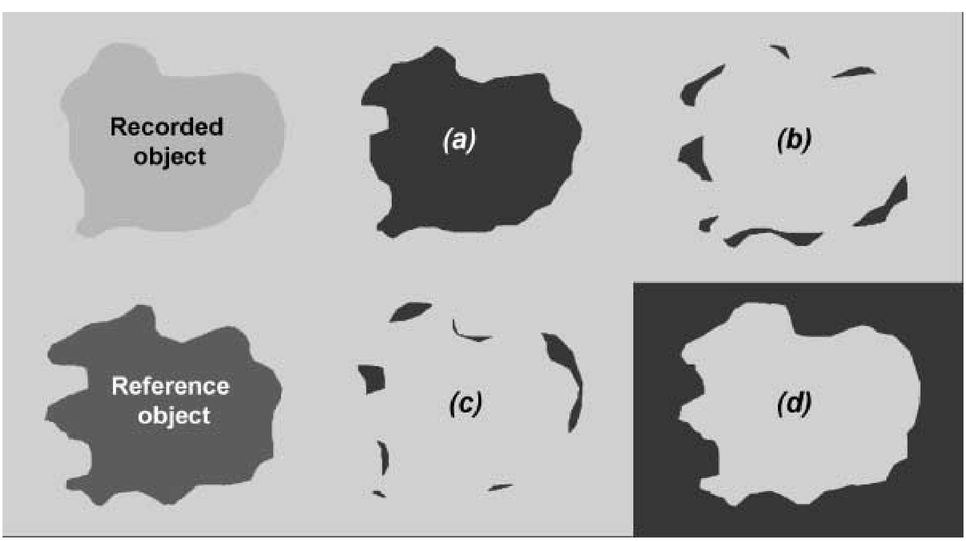

Figure 5 Basic idea of map comparison for assessing classification uncertainty (dark coloured object class identified: (a) in both objects, (b) in the reference but not in the recorded object, (c) in the recorded but not in the reference object, (d) not in both objects)

design (Stehman and Czaplewski 1998, Stehman 1999). These measures provide useful knowledge about uncertainty aspects of the classification (see Fielding and Bell 1997 and Foody 2002 for reviews in land cover classification) and are generally derived from pixel-based approaches. Due to some disadvantages of these measures, alternative statistics have been introduced recently, such as Kappa for quantification error or Kappa for location error (Pontius 2000).

Traditional techniques of accuracy assessment do not allow for prediction of vagueness. They only describe the occurrence of one class per pixel definable in space and attribute – a Boolean occurrence of units. Furthermore, they provide statistical measures rather than spatially oriented assertions. Recently, these approaches were extended to assess area estimates from generalised confusion matrices (Lewis and Brown 2001) or to derive local summary statistics for geo-statistical analysis (Brunsdon et al. 2002). Despite the limitations mentioned, such methods provide valuable information about uncertainty inherent to the data base.

Methods for *discrete uncertainty modelling* imply basic ideas such as error bands and epsilon bands (Perkal 1956, Goodchild and Hunter 1997) or confidence regions (Shi 1998) in vector representations or rough sets in pixel representations (Ahlqvist et al. 2000, Fisher 2001). Such approaches consider the variation of the object geometry and are thus more related to the amount of positional uncertainty of boundaries (Figure 6a). One problem is the lack of information about the inner spatial variation of uncertainty. Another one is the assumed homogeneity of attributes and thus the missing consideration of indeterminacies within an entity. With regard to natural phenomena not only boundaries but each location of the object have to be treated as uncertain or fuzzy.

Some of these disadvantages can be solved through the application of *fuzzy sets* (Zadeh 1965; see Robinson 2003 for an overview of fuzzy sets in GIS). These techniques allow the consideration of the spatially varying uncertainty of natural objects with regard to the entire entity. Thus it relates to the aspect of vagueness due to poor definition.

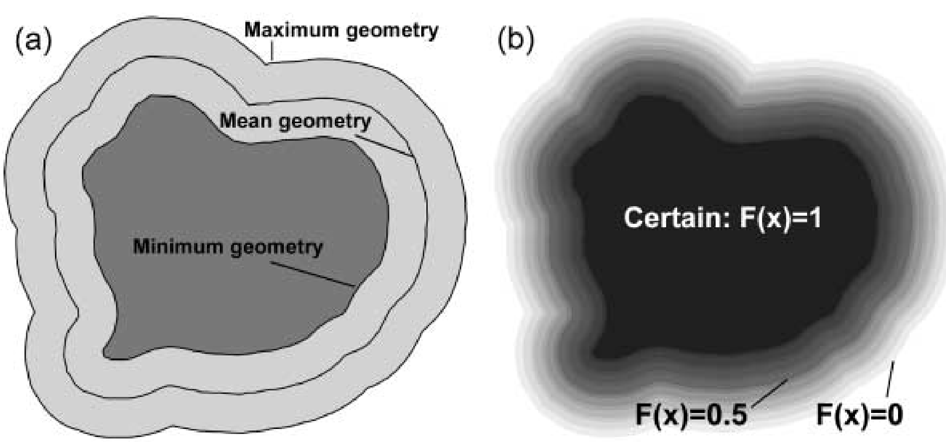

Figure 6 Basic idea of discrete uncertainty modelling (a): the positional error is defined by the deviation of the geometry between the considered object and the reference object inward and outward; basic idea of uncertainty modelling using Fuzzy Sets (b): each location of the object is defined with a degree of membership by a membership function F(x)

For each location of an object a membership value in the real number range from 0 to 1 is defined on the basis of a membership function (Figure 6b).

This value indicates the degree to which the phenomenon matches the characteristics of a prototype concept. The form of the function often depends on subjectivity or a priori knowledge (Burrough and McDonnell 1998, Fisher 2001). The semantic model which has been derived from the reference map is thereby of great use. Every location can be defined by a specific membership value expressing the degree of truth which is related to vagueness.

The methods described all provide useful information about the inherent uncertainty but have different limitations. There are alternative approaches in which these methods are combined to obtain more sophisticated solutions for map comparison procedures. Supervaluation has been suggested as an alternative to fuzzy sets (Bennett 2001, Kulik 2001) but provides no quantifiable results. Combinations of confusion matrix approaches and fuzzy set operations (Jäger and Benz 2000, Woodcock and Gopal 2000, Hagen 2003) were shown to be flexible methods for map comparison if spatial entities have vague definitions or multi-memberships. Furthermore, the integration of rough and fuzzy geographical data into a unified representation has been proposed (Ahlqvist et al. 2003).

4.2 Transformation-oriented Uncertainty

4.2.1 General Aspects of Transformation-oriented Uncertainty

A historical map usually exists in paper form. Thus to incorporate the historical geographical data into a GIS as a digital product several steps have to be realized. Each of them bears potential sources of uncertainty. This aspect is often referred to as processing error (Goodchild 1991) but will be called transformation-oriented uncertainty in this paper. Lineage, which in this case addresses the stages of transformation and data editing, provides valuable information for the evaluation of scanned historical maps. Some of the mentioned stages are:

- The conversion from analogue into digital data (digitisation) by scanning. Its quality depends on resolution, modification of colour space and on the distortion of the original map caused by age or humidity.
- The process of geo-referencing. In this example, to convert the old datum of the Berne projection into the present Swiss national coordinate system an interactive affine transformation procedure was applied. Thereby, reference points such as churches, bridges or road junctions existing in both the historical map and the present Swiss national topographic map were used. Since the maps do not perfectly agree this procedure causes errors which can be quantified by measures such as root mean square error (RMSE).
- Object extraction and vectorisation of the objects of interest. Usually, historical maps were produced manually. Consequently, graphic symbols are characterised by high variability in size, form and colour. The extraction of the digital data of interest requires therefore in many cases sophisticated pattern recognition methods. In applying such automatic or semi-automatic procedures additional errors occur, which can be analysed by comparing the extracted data against the digital data source they were derived from.

The contents of the digital database are supposed to be translations of the analogue map. The representations of objects in the analogue data source are thus understood as indicating the true states of objects to be transformed. Therefore, they can be considered as well-defined entities with sharp boundaries according to their representation in the map independently from the nature of the real world. Transformation-oriented uncertainty corresponds to the deviation from these representations caused by technical procedures. Thus its resulting amount is characterized by positional uncertainty or uncertainty due to incompleteness. The knowledge of the true state and the possibility of repeated measurements allows the application of stochastic and probabilistic approaches and refers thus to the concept of error (Figure 8). It usually implies the possibility of controlled analysis and quantification. Attention has to be paid where the concept of error is not suitable. One example is the determination of a boundary which is not mapped as a crisp entity but indicated through distribution of single graphic symbols. In these cases different concepts such as vagueness due to interpretation may be appropriate to define or narrow down this boundary. However, the transformations and editing procedures are preconditions for the digital analysis of the production-oriented uncertainty in GIS.

So far the distinction between production- and transformation-oriented uncertainty is valid for cases in which the production of the map and subsequent transformations of the digital data represent separate working steps. In cases where the historical map has been created digitally on the basis of digital aerial or satellite images production- and transformation-oriented uncertainty are inseparable and have to be understood as one complex domain.

4.2.2 Assessment of Transformation-oriented Uncertainty

In general the amount of processing error is expected to be significantly smaller than the amount of production-oriented uncertainty. In such cases it can be considered to be secondary. Nevertheless, its investigation has to be included in a complete analysis of historical maps to understand the complex nature of uncertainty.

Basically, the amount of transformation-oriented uncertainty is estimated by comparison of the digital data to the source document from which they were derived. All methods described for the assessment of production-oriented uncertainty can be applied in this domain. The characteristics of transformation-oriented uncertainty as described above, however, allow the application of stochastic approaches (Goodchild et al. 1992, Drummond 1995) or probabilistic methods (Fisher 2001, Foody 2002) for positional error modelling. Methods such as error bands (Figure 7) or confidence region error bands for modelling the positional error of line segments in a vector GIS (Shi 1994) have been well developed. One example is the G-band model (Shi and Liu 2000) for analysing the positional error of line segments which is based on stochastic process theory. Analysis of the positional error of polylines or polygons is based on models for line segments. However, such methods are not yet widely adopted (Zhang and Goodchild 2002).

Each of the transformation procedures provides an independent error. To estimate the total processing error a cumulative effect has to be acquired. This cannot be derived by simple addition since the single components are overlapping. There are also problems in keeping apart the effects of production- and transformation-oriented uncertainty if analysing the derived digital data in a GIS. For example, the error of geo-referencing procedures of the digital data can often not be distinguished from spatial effects due to the historical field survey. In such cases it is important to find confident reference points in both the historical and the present-day map. After the cumulative processing error

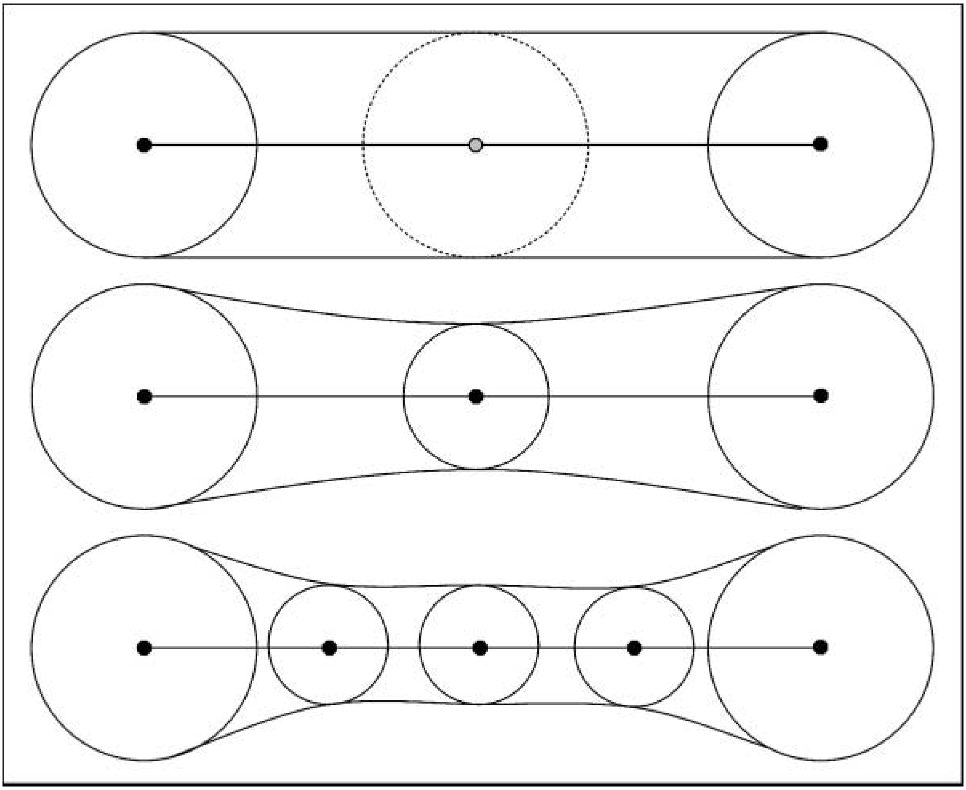

Figure 7 Basic idea of error bands for analysis of positional uncertainty of line segments (based on Shi and Liu 2000)

has been derived, quantitatively, it can be compared with the amount of production-oriented uncertainty from domain one.

4.3 Application-oriented Uncertainty

4.3.1 General Aspects of Application-oriented Uncertainty

In order to use the data collected from historical maps in target applications such as land cover change modelling, it has to be ascertained that the object represented in the map also matches the intended use in our target application. There is evidence of uncertainty dependent on this intended use (Gottsegen et al. 1999) which can thus be called application-oriented uncertainty (Figure 3). In comparing historical map information with present-day data, uncertainty arises due to different (semantic) meanings of objects. This is related to differences between the intended use and the original use of the historical map. In other words, semantic incomparability or incompatibility between historical and present-day data causes uncertainty and thus inadequacy of the historical data for the intended application. Possible consequences are wrong results or wrong interpretation of results in spatial analysis. Therefore, the evaluation of uncertainty in this domain has to be seen as a precondition for the subsequent target-application.

One occurring aspect is ambiguity, i.e. the confusion over definitions of entities (Figure 1). It concerns the definition of landscape elements and their boundaries from two different data sources. Thereby 'multi-temporal' or application-oriented discord arises owing to different inconsistent classification systems used for the objects which are supposed to have the same meaning (Figure 8). The assessment of application-oriented discord assumes clearly defined objects to realise a comparative analysis.

The derivation of definitions used for the mapping of natural phenomena in historical maps is a matter of production-oriented uncertainty. As mentioned above, the semantic model of the object of interest which is usually derived from the reference information is used to assess semantic uncertainty in the map of investigation. This uncertainty describes the deviation from the selected model and thus allows the derivation of a specific definition which is valid for the mapping of the considered phenomena. It corresponds to the concept of non-specificity which relates to the problem of subjective interpretation in definitions and instructive elements from the social environment, as described above. In terms of ontology it is the result of social influences such as instructions and of subjective knowledge that the creator or agent has about the real world. As mentioned, semantic uncertainty includes further concepts. Consistency refers to equi-temporal discord as a measure of internal validity over the entire historical map. Attribute uncertainty, incompleteness and currency are further important criteria to define a mapped landscape element in general or semantic terms. However, the semantic model can only be explained by including the conceptual entities which the creator derived from observation within the real world to represent it in the map. This link to the production-oriented component of uncertainty is fundamental to the understanding of the nature of application-oriented aspects.

4.3.2 Investigation of Application-oriented Uncertainty

The investigation of the uncertainty dependent on the application implies a comparative analysis of definitions used for landscape elements in two different data sources, the historical one and the present-day one. Thereby, criteria such as quantitative measures or descriptive features indicating the semantic term for the considered object are compared to examine the agreement of the used classification systems. The resulting 'multi-temporal' inconsistency or multi-temporal discord indicates the degree of incompatibility between the definitions. If this is not acceptable the data have to be examined to determine whether they can be semantically modified to find a term which is valid for both data sources. This is done through generalisation, simplification or abstraction of the classification systems. Thereby, it is possible that only a part of mapped objects can be applied to land cover change models since compatibility can only be ensured for that part. However, the compatibility between compared data represents a fundamental precondition for confident applications. Application-oriented uncertainty results in a statement whether or not the data are adequate for the target application or narrows down the range of data which is comparable.

The effort to derive the definition used for an object in a historical map greatly depends on the objective of mapping and the age and also on the availability of reference information such as photos or local maps. The older the map, the lower the detail of definitions is for natural objects within it. It can be characterised by subjectivity if interpretation is involved (relation between social reality and subjective knowledge in Frank 2001). The derived definition of the object should include some applicable rules such as measures of minimum area and extent of transition zones, estimations of

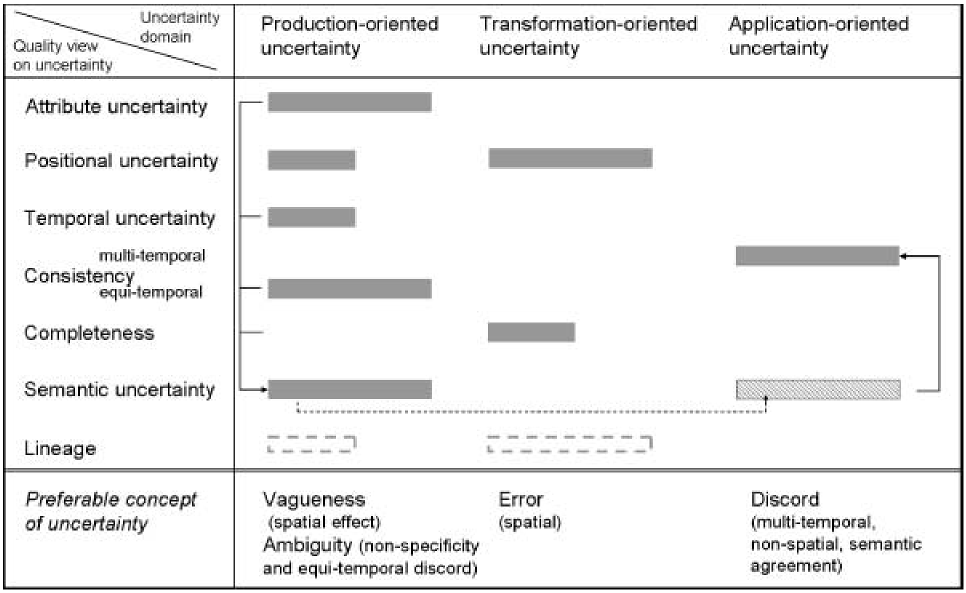

Figure 8 Relationships between uncertainty forms derived from data quality, uncertainty domains and suitable concepts of uncertainty within these domains (grey boxes indicate importance within the domain relative to size, hatched boxes indicate importance also for a different domain connected with dashed arrows from their origin, closed arrows illustrate the deduction of one complex aspect, dashed boxes represent rather descriptive elements)

consistency over the entire data source or other descriptive notes. In general, the definitions used for present-day landscape assessments underlie well-defined terms, which limit this investigation to the historical map.

4.4 Overall Amount of Uncertainty and Assessment of Fitness for Use

To ensure the appropriateness of geographical information for a certain application one has to make sure whether the occurring effects of error and uncertainty are acceptable or not. To realise objective decision-making the assessment of fitness for use has to be carried out. Risk-based procedures (Agumya and Hunter 1997, 1999) of fitness for use propose the amount of uncertainty to express the existing risk in the final decision the user has to deal with. Risk is defined as the probability that an adverse event will occur or as the cost or consequences of that event (Agumya and Hunter 1997). Since there is a link between risk and uncertainty, risk is attributable not only to uncertainty in the information but also in the applied decision rules. Consequently, the quality of decisions and not only the quality of information is accessible. Practically, the existing risk has to be compared to the acceptable risk formulated by the decision-maker to assess fitness for use (Zhang and Goodchild 2002). In this case the overall amount of uncertainty in using the historical data for the described target application is compared to an acceptable amount which is formulated by the user.

The presented conceptual model provides a systematic and practicable frame to analyse the amount of uncertainty in different domains by exposing all potential sources of uncertainty. To express the overall amount of uncertainty an understanding of its complex nature is required. Since the single aspects of uncertainty derived from different domains show specific characteristics they have to be compared separately with their accordingly acceptable values.

The assessments of production- and transformation-oriented uncertainty result in quantitative or even spatial measures. As mentioned, the former is generally expected to be larger than the latter. Owing to possible overlaps between both aspects they cannot be added to each other. If there is significant difference between them, the smaller effect can be considered to be secondary – the larger one to be dominant. In cases where production stages and transformations of digital data are not separated, the amounts of uncertainty in domain one and two have to be treated as one combined domain. The investigation of application-oriented uncertainty semantically describes the adequacy of the data for the target application as an important precondition.

There is evidence of the general validity of the conceptual uncertainty model in the context of evaluating historical map information prior to using it on target applications like land cover change modelling. The investigation of uncertainty in different domains represents the basis for a systematic, practicable and complete investigation procedure. This can be applied to any other historical data source which is intended for a particular target application of land use or land cover change modelling. The amount of uncertainty and its nature have to be considered for objective model validation of conducted land cover change models.

5 Application of the Framework to a Case Study

In this section, a practical application of the described framework is described for demonstration purposes. Some results derived from analyses of several test sites are presented to show the complex nature of occurring uncertainty and to give an idea of the quantity of different aspects. The forest cover from the historical map which is described above is thereby used for the establishment of a forest cover change model in Switzerland. The change in forest cover is determined by comparing historical data to present-day forest assessments. To assess fitness for use of the data for this application, the existing risk, which is related to the overall amount of uncertainty, has to be determined beforehand. The age of the historical map makes it possible to clearly separate different aspects of uncertainty into the different domains of the presented framework.

5.1 Production-oriented Uncertainty

The quantitative pixel-based comparison of the Siegfried map and the reference maps resulted in global accuracy measures (PCC between 0.78 and 0.82, Kappa between 0.57 and 0.63) which indicated agreement to a certain degree (Table 1). The single pixels were used as sample units in a systematic distribution to cover the entire area (formulae from Foody 2002). However, these measures do not provide information about the spatial distribution of inherent uncertainty and the results are limited to the area covered by the reference map. It was found that uncertainty varies throughout the area depending on topographic conditions, indicating the existence of a relationship. The calculation of measures from confusion matrices within different strata, which are derived from classes of slope or elevation, showed a decrease in accuracy with increasing slope or elevation (Table 1).

Table 1 Selected results of the case study. Uncertainty assessments within different domains of uncertainty and some interpretations of the results obtained

Domain of uncertainty	Source of uncertainty	Assessment of uncertainty	Results	Interpretation
Production-oriented uncertainty	Spatial effect of uncertainty from data collection and map production	Statistical measures from global map comparison with reference maps	PCC = 0.78–0.82 Kappa = 0.57–0.63	Agreement between maps without spatial orientation and consideration of variation of uncertainty over the area
		Statistical measures from stratified map comparison with reference maps (example for strata of *slope in degree*[°])	*Stratum* *PCC* *Kappa* 1 (0–10°) 0.87 0.67 2 (10–20°) 0.81 0.61 3 (20–30°) 0.75 0.35 4 (30–75°) 0.67 0.27	Decreasing agreement between both maps with increasing topographic gradients indicates some relationship to the amount of uncertainty
		Predictive uncertainty modelling using local summary statistics and GLM (see Leyk and Zimmermann 2004 for details)	Explained deviance by the model (D^2): 40 percent Correlation between predicted and observed values: 0.76 Improvement of the model (G-value): 47 percent	Significant relationship between explanatory variables and local uncertainty; Prediction potential for uncertainty at any location and its variation over the area
	Lack in knowledge about the used semantic model (table 2 for details)	Historical investigation to construct a forest term which fits the historically mapped objects, semantically	Forest term/definition indicating a semantic model used for historical forest mapping	Understanding of the used term for identifying forest in the field in the 19th century

Table 1 Continued

Domain of uncertainty	Source of uncertainty	Assessment of uncertainty	Results	Interpretation
Transformation-oriented uncertainty	Scanning of paper maps	Distortion check	0.1–0.3 percent (depending on the equipment)	Positional error due to distortion
	Geo-referencing (affine transformation)	RMS error as distance between input coordinates and retransformed reference coordinates	RMSE between 8.0 and 15.6 m depending on the region (midlands or high mountains)	Inner distortion of the map or lack in geodetic accuracy of the historical coordinate system
	Pattern recognition for object extraction	Statistical global measures from map comparison	PCC = 0.87–0.98 Kappa = 0.83–0.96 (depending on the region)	Degree of agreement between the extracted classes and original classes in the map
		Error bands	Confidence intervals for boundaries which are not suitable for this problem	Positional uncertainty along boundaries, but any location is prone to classification error
Application-oriented uncertainty	Incompatible historical and current data	Comparative analysis of the semantic models of both data sources	General forest term/definition which fits the meaning of forest in both data sources	Only the forest area which fits the general definition can be used for land cover change modelling

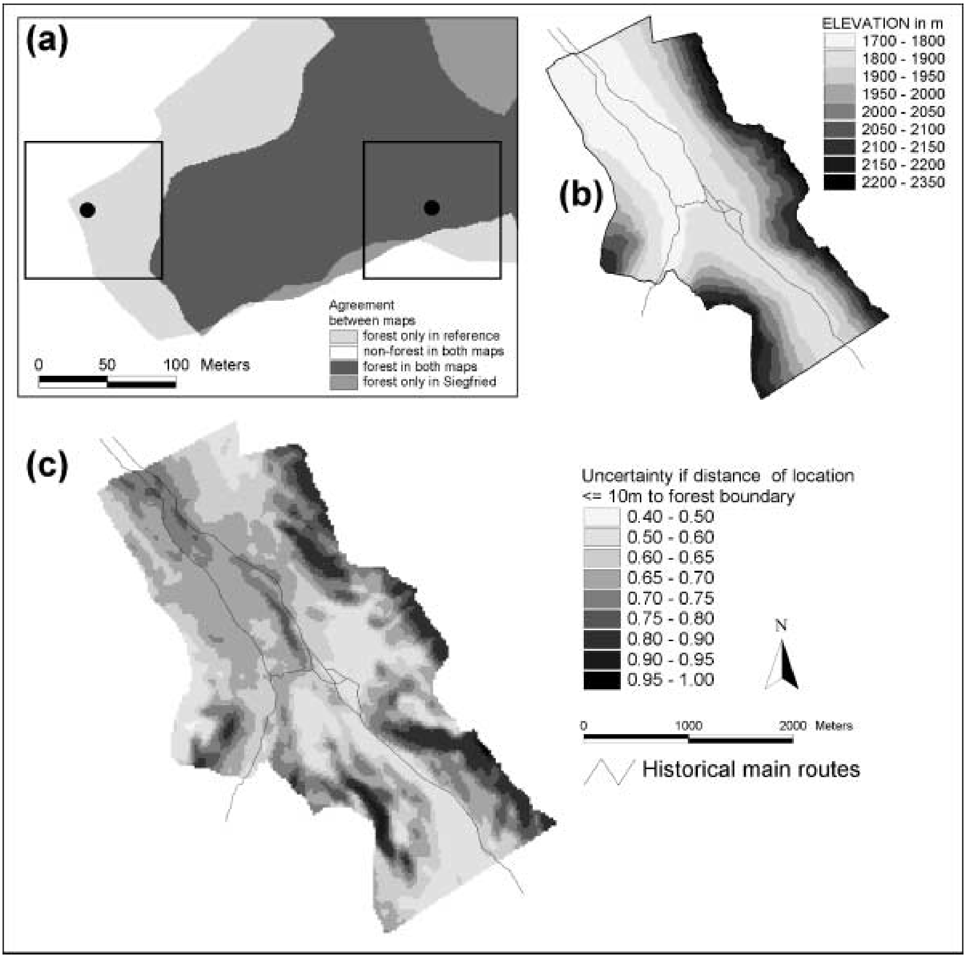

Figure 9 Illustration of the construction of a predictive uncertainty model using Generalized Linear Models and data from a test site in the high mountains. The dependent variable is assessed as local uncertainty from local map comparisons within moving windows (a). Topographic gradients such as slope, elevation or distance to old road networks are incorporated as explanatory variables (b). The models allow the prediction of the amount of uncertainty at any location and its variation over the area (c). See Leyk and Zimmermann (2004) for details

Leyk and Zimmermann (2004) present the development of a predictive model for mapping the *inherent* uncertainty of the forest cover in areas which are not entirely covered by reference maps (Figure 9). To enable this, the knowledge of the amount of uncertainty and its variation in space, as evaluated from a limited number of local reference maps, needs to be extrapolated to the whole historical map. They develop Generalized Linear Models (GLM), which link the local uncertainty to a set of generally available predictors, allowing the extrapolation of these linkages into space or to areas not covered by the reference maps. Thereby it is hypothesized that the errors of such mapping efforts can be related to a set of topography-dependent predictors such as slope, aspect and elevation, as well as distance and visibility from old road networks (Figure 9). These explanatory variables represent factors that are assumed to have been limiting factors for field based surveys, such as visibility or accessibility. The rules they found best describe the quality and the associated errors of topographic field mapping during the nineteenth century. The uncertainty measures (local Kappa and local PCC) are derived from local summary statistics within moving windows of varying sizes which are systematically distributed (Figure 9). Thus the measures indicate local disagreement which compensates spatial distortion to a certain degree and allows for a spatial-oriented determination of local uncertainty.

In this approach, models fitted with uncertainty measures from 100 m windows best described the relationship to the explanatory variables and showed significant prediction potential. The explained deviance by the Kappa-based model of more than 40 percent and the high correlation between predictions and independent observations of $\rho = 0.76$ resulted in an improvement of the model to 47 percent, indicated by the G-value (Table 1; details presented in Leyk and Zimmermann 2004). The models allow the spatially-oriented prediction of *inherent* uncertainty within different regions of comparable conditions.

Such analyses provide useful information for the definition of fuzzy membership functions indicating the degree of inherent uncertainty for each location. These functions can be used in landscape change modelling. In this analysis only the spatial effect of production-oriented uncertainty can be considered. For more objective analysis the semantic uncertainty in the historical map relative to the selected model in the reference map has to be incorporated. This investigation is described below in relation to application-dependent aspects.

5.2 Transformation-oriented Uncertainty

The nature of error modelling has been described above. In this case study, error is introduced mainly by scanning, geo-referencing of the historical map and methods of object extraction. Scanning and geo-referencing are dependent on the technical parameters and methods applied. The error occurring from scanning the historical maps with a resolution of 250 dpi can be estimated between 1 and 3 percent, depending on the equipment used. The RMSE resulting from geo-referencing was between 8.0 and 15.6 m using the affine transformation procedure. The results are given in Table 1. Object extraction will be considered in more detail since it represents the most complex process.

Object extraction of the forest cover from the Siegfried map is realised by methods of digital pattern recognition. This is necessary because of high variability of graphic symbols for forest in shape, size and colour as a consequence of the manual production of the map. The two-dimensional spatial information is represented by the irregular distribution of these symbols. The forest boundary is indicated as a black line for closed forest (Figure 2) and not mapped for open stands. Methods of pattern recognition try to recognise and classify these graphic symbols to derive the spatial information of forest cover. Figure 10 presents the result of the comparison of the extracted forest cover and the manually vectorised forest cover from a test site. The validation of the procedure using pixels as sampling units in a systematic distribution shows high accuracy (PCC = 0.98, Kappa = 0.96, see Table 1). It decreases in areas where the quality of the document decreases (PCC ~0.87, Kappa ~0.83) due to lack of separation of graphics. For manual vectorisation the central pixels of the mapped boundary are used. Edges of open

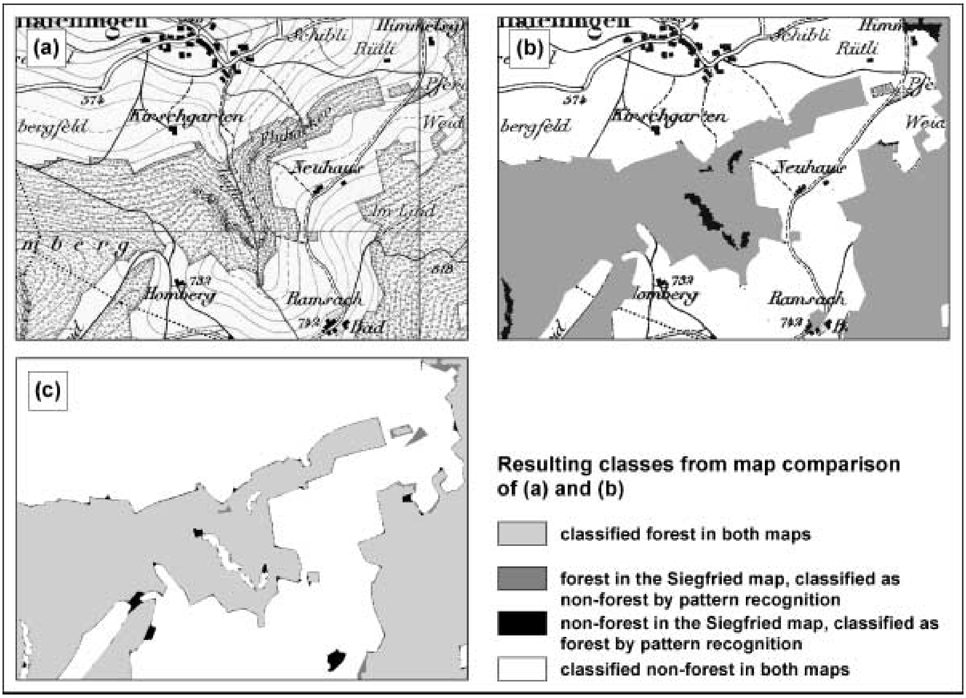

Figure 10 Quantitative map comparison (c) of the extracted forest area by pattern recognition methods (b) and the original forest cover in the map (a), illustrated by the analysis from a midland test site

forest stands on the upper tree line or in cases of wood pasture were determined by interpretation. To improve this decision–making, expert questionnaires can help to find objective definitions of the boundary.

5.3 Application-oriented Uncertainty

Prior to the performance of the comparative analysis between historical and present-day forest definitions the historical term used for the identification of forests during the mapping in the nineteenth century is needed. As described above, this is done by evaluating the semantic distance from the selected model to assess production-oriented semantic uncertainty. This model is taken from the reference map since the entire assessment of production-oriented uncertainty is carried out based on them.

In considering forest cover which has been mapped more than 100 years previously a historical investigation requires great effort. The amount of available information considering the mapping of forest during the nineteenth century is very limited and instructions were formulated without detailed consideration of the nature of forests. Thus the investigation implies historical aspects of forestry, agriculture, topography, politics and society in general (social reality) at the end of the nineteenth century to identify important streams and influences prior to and during the topographic fieldwork (Table 2). The consideration of all these aspects allows for an interpretational approach. It starts with a general understanding of attitudes towards the environment and nature

Figure 11 Historical photo, which is included in the analysis to derive a historical forest definition (source: Bühler J. 1938). This picture shows an Alpine landscape in the beginning of the 20th century where large patches of forest have been removed for agricultural use

in society (Walter 1989). It ends at the particular consideration of forest and at the specific situation of a topographer in the field identifying forest (subjective knowledge). Local maps, forest management plans or early photographs (Figure 11) from the same time period are essential to derive a semantic term for forest. Once this term is achieved for the reference map the definition used in the topographic map being investigated can be determined by estimating the semantic difference between these two sources.

A forest definition includes different criteria such as the minimum area (completeness) of mapped forest, the maximum size of non-forest areas which are not considered within the forest (1.4 and 0.8 ha for the example in Table 2, respectively) or estimations of density to differentiate closed and open stands (attribute aspects). Typical characteristics such as forest types, management systems or non-timber forest uses such as temporary agricultural use of clearings or wood pasture have to be taken into account. Accordingly, regional differences have to be investigated (consistency). The considered period between 1870 and 1900 marks the beginning of federal forestry legislation in Switzerland. In this context, changes in societal demands which were related to changes in forest use during the nineteenth century makes such an analysis interesting. Table 2 presents a short summary of the aspects described which are useful for the historical analysis of a forest definition.

To assess data compatibility the comparative analysis of the derived historical and the current forest definition is carried out. The objective is the establishment of a term

Table 2 Example of an evaluation matrix for determining a historical forest definition (semantic model) from historical information, reference material and social contexts; criteria are collected for different regions (here midlands) to meet the heterogeneity of forests in Switzerland in the nineteenth century

Region	Criteria	Indicators	Values/Descriptions
Midlands	Forest in the map as a topographic appearance (from reference maps and historical photographs)	Smallest unit of forest mapped	1.4 ha
		Largest area of not considered gaps within the forest	0.8 ha
		Consideration of all property categories	private/public
		Density (site index) (estimated values)	open forest in the map: <0.4 closed forest in the map: >0.4
	Forest characteristics in the 19th century – a historical appearance (from forest history, landscape history, literature, . . .)	Forest types (appearances; estimated proportions)	Simple coppice forest (20 percent) Coppice-with-standards forests (15 percent) High forest (65 percent)
		Management systems (critical for definition)	Clearings in high forests (counted as forest)
		Non-timber forest uses practised	Temporary agricultural use of clearings
		Effects from earlier non-timber forest uses	Wood pasture
		Forest boundary (dependent on neighbourhood)	Frequently transition zones (succession) if marched upon agricultural land
	Social construction of the forest (cultural, political and economic influence)	Institutional influences from forestry, law and politics (power of legitimisation)	Legislation concerning forest, its treatment and use
		Collective attitudes towards the relationship society-forest (nature)	Landscape protection vs. risk perception, economic value, politics, education and science for construction of the meaning of forest
		Group-specific perception of forest based on personal background, knowledge and influences	Representation of forest in the map, undercarried by the group of map makers

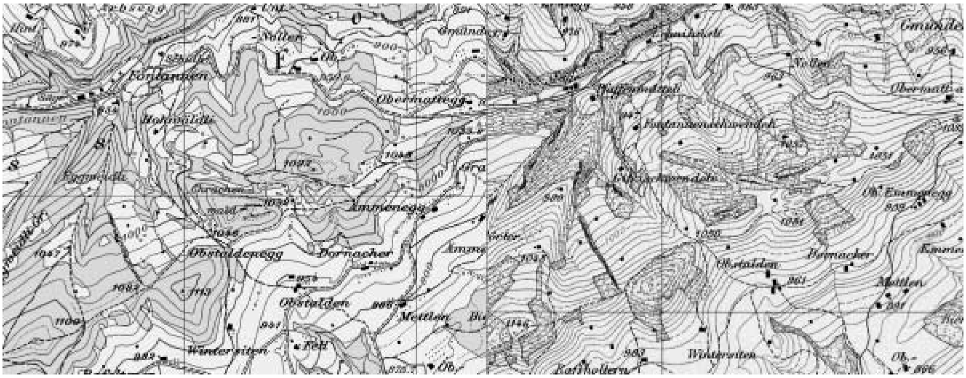

Figure 12 The current (i.e. up-to-date) Swiss topographic map, © 2004 swisstopo, (left) and the Siegfried map (right) will be compared for an area-oriented approach of forest cover change modelling

which unifies the characteristics of forest in both data sources. If the compatibility is not satisfactory, the derived terms have to be simplified, generalised or even modified. The results of this preliminary study already show that several categories of forest in the present day data source (such as closed forest, open forest and bush forests) have to be aggregated to one general forest term to conform to the historical forest term. Furthermore, since the minimum area of mapped forest units seems to be significantly larger in the historical map only units above this threshold can be considered for the analysis of cover changes. If certain features mapped as forest occur in the historical map which today would not fulfil the definition of forest this information is essential for objective interpretation of subsequent results. One example is the occurrence of temporary agricultural use of clearings during the nineteenth century.

5.4 Forest Cover Change Model as Target Application

As described the target application in this study is the establishment of a forest cover change model. The analysis of uncertainty using the presented framework is one precondition for objective interpretation of modelling results. Thus, on the one side, the spatial effect of production- and transformation-oriented uncertainty has to be incorporated into spatial analysis. The modelled change of the forest cover at one location has to be indicated by the degree of uncertainty in the historical information. On the other side, only objects from both maps which are supposed to have the same meaning are considered and compared.

In our case, two approaches of forest cover change modelling are intended. The comparison of the historical information with the forest cover of the up-to-date topographic map of Switzerland (Figure 12) allows the realisation of an area-based approach. Thereby, the present-day data source also has to be considered with regard to uncertainty since it represents natural phenomena as crisp objects. In this approach the change in forest cover and the occurring uncertainty at an exact location can be assessed.

A second approach is the comparison of the historical data with the point-wise assessments of the Swiss National Forest Inventory (NFI). Thus a point-based approach is realised. The decision-making whether a location belongs to forest or non-forest has to be simulated at each point of the NFI grid which covers all of Switzerland. This decision requires practicable rules such as minimum distance to the next forest boundary to incorporate uncertainty, adequately.

6 Discussion

The example in section 5 demonstrates the application of the framework to a real-world case of landscape change modelling. Thereby, different domains of the framework are derived from the components of a GIS. Existing relationships between components of spatial data quality and common concepts of uncertainty facilitate the assessment of uncertainty within each domain as described in section 4. By using these domains, the researcher or user, who is frequently unaware or feels uncomfortable in assessing uncertainty in its entire complexity (section 2), can rely on a structure which is known within the GIS community. This is an attempt at facilitating access to the field of uncertainty handling in GIScience for the application-oriented researcher. Within each domain the investigation of uncertainty by applying suitable techniques is described. Some techniques are proposed in section 4, which match the deduced concepts, such as error, vagueness or ambiguity and thus the nature of occurring uncertainty in different degrees (see sections 4.1 through 4.3).

The example emphasises the interrelation between the three domains. It becomes obvious that the analysis of the production-oriented uncertainty, as described in section 4.1 alone does not provide sufficient evidence to evaluate the database in relation to the target application. It only accounts for the amount of uncertainty due to vagueness, discord and non-specificity which are inherent in historical data. Prior to the analysis of this inherent amount in GIS, the assessment of the transformation-oriented uncertainty through error analysis has to be performed, as described in section 4.2. This error has to be known to improve the analytical procedure and in order to compare it with the production-oriented spatial effect of uncertainty. As a consequence, the error introduced during transformation or extraction of the information can be estimated. In other words, while the production-oriented amount represents an unchangeable feature of the map, the transformation-oriented error describes the part of the spatial effect of uncertainty which can be influenced and measured repeatedly within the controlled environment.

So far the spatial effects due to error and vagueness are valid for the landscape element which is represented in the historical map. The necessity of semantic convergence between the historical and the present-day objects has been discussed in relation to the subsequent target application. As the example shows, the semantic models from different data sources have to be compatible for comparison. If the definitions for the landscape element considered do not agree, a selection of objects from both data sources has to be found, which can be considered as semantically equal. Only this selection is to be incorporated into landscape change models. Thus, the amount of application-oriented uncertainty plays a key role for the analysis of landscape change.

The way in which historical data can be used in the target application depends on the level of uncertainty within the single domains. In the scope of assessing fitness for use of the data, as described in section 4.4, the user has to formulate acceptable values in relation to semantic compatibility, to the error introduced by transformations and data handling as well as to the spatial effects of uncertainty inherent in the historical map. The user is thus responsible for the confidence of his or her model of landscape change and for the level of the objectivity of the results. This depends on whether he or she provides the information of uncertainty which is still within any of the three domains. The framework thus provides a suitable platform for systematic and complete investigation and documentation (e.g. in metadata) of uncertainty as arising from the sources described above.

7 Conclusions

Historical maps provide important data sources for applications in change detection and land cover change models. Due to the various aspects of uncertainty involved in processing these data sources, however, advances in extracting spatial information from historical maps and in incorporating them into land cover change models depend on the availability of suitable conceptual approaches for uncertainty investigation. This implies the improvement of the theoretical background of uncertainty handling in GIS and the establishment of comprehensive definitions of key concepts.

The conceptual framework presented in this paper allows the systematic investigation of uncertainty not only in the information extracted from historical data sources but also with respect to data handling and the use in the subsequent target application. In section 4 it is argued that systematic investigation must expose all the potential uncertainty sources occurring in different domains. These domains are derived from components of constructing a GIS and are thus called production-, transformation- and application-oriented uncertainty, respectively. It is argued that this process-based view facilitates the access to the field of uncertainty by referring to a structure which is familiar to GIS users and researchers. Within each of the three uncertainty domains the identification of existing sources of uncertainty has been shown. To describe the occurring amounts of uncertainty which arise from these sources, suitable concepts or types of uncertainty and their relationships to aspects of spatial data quality have been presented. This procedure implies a comprehensive understanding of the nature of uncertainty and basic analytical procedures.

This paper shows the importance of such conceptual approaches. The applicability of the framework is demonstrated in a case study. Thereby, the distinction of three different domains was shown to be a suitable basis for a systematic procedure. This is necessary for the investigation of the overall amount of uncertainty in its entire complexity, which has to be considered prior to conducting the target application. The structure of the framework shows a flexibility which allows an adaptation to different conditions and application contexts. The general validity for related cases can thus be assumed. Additional approaches of uncertainty modelling in spatial databases such as in Morris (2003) or further sources of uncertainty such as in spatial queries (Wang 2003) can be linked to the framework.

Existing parallels between data quality research and uncertainty assessment were shown to be very useful for a transparent and comprehensive derivation of concepts of uncertainty. To avoid confusion, an attempt was made at establishing definitions for these concepts. Based on ontology of geographic information (Frank 2001) and cognitive principles (Mennis et al. 2000) it was intended to improve the understanding of such definitions of concepts. However, further research should be dedicated to such issues to strengthen the theoretical background of uncertainty in treating it as an integral part of geographic data.

Furthermore, future research work should include the consolidation of the demonstrated conceptual contexts by referring to additional application examples. These additional case studies are expected to provide more practical evidence by applying a wider range of different techniques of uncertainty analysis. The examination of links to the assessment of the fitness of the data for the intended use (Agumya and Hunter 1999) will be of particular interest.

As Couclelis (2003) recently mentioned, 'the days when people thought that science meant certainty are well behind us'. Uncertainty in geographical information today has to be considered as an integral part which 'is built into our knowledge production process' (Couclelis 2003, p. 173). Although significant research in the field of GIScience is presently being undertaken to assess, measure, represent and reduce uncertainty, there is always something left one cannot know. For future scientific work the awareness of uncertainty and the understanding of its complex nature are important issues to derive objective and reliable results from spatial analyses. With this paper, the authors have tried to contribute to this ongoing discourse by exploring what can be known and improving our awareness of what cannot.

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Paper III

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A Predictive Uncertainty Model for Field-Based Survey Maps Using Generalized Linear Models

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Abstract. In this paper we present an approach for predictive uncertainty modeling in field-based survey maps using Generalized Linear Models (GLM). Frequently, *inherent* uncertainty, especially in historical maps, makes the interpretation of objects very difficult. Such maps are of great value, but usually only few reference data are available. Consequently, the process of map interpretation could be greatly improved by the knowledge of uncertainty and its variation in space. To predict *inherent* uncertainty in forest cover information of the Swiss topographic map series from the 19th century we formulate rules from several predictors. These are topography-dependent variables and distance measures from old road networks. It is hypothesized that these rules best describe the errors of historical field work and hence the mapping quality. The uncertainty measure, the dependent variable, was derived from local map comparisons within moving windows of different sizes using a local community map as a reference map. The derivation of local *Kappa coefficient* and *percent correctly classified* from these enlarged sample plots takes the local distortion of the map into account. This allows an objective and spatially oriented comparison. Models fitted with uncertainty measures from 100m windows best described the relationship to the explanatory variables. A significant prediction potential for local uncertainty could thus be observed. The explained deviance by the Kappa-based model reached more than 40 percent. The correlation between predictions by the model and independent observations was ρ=0.76. Consequently, an improvement of the model to 47 percent, indicated by the G-value, was calculated. The model allows the spatial-oriented prediction of *inherent* uncertainty within different regions of comparable conditions. The integration of more study areas will result in more general rules for objective evaluation of the entire topographic map. The method can be applied for the evaluation of any field-based map which is used for subsequent applications such as land cover change assessments.

1 Introduction

Historical spatial information frequently represents essential input for landscape change analysis in geographical information systems (GISs). In this context, historical maps are unique witnesses of past landscape configurations. They provide histori-

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cal information on a landscape before aerial photography. The potential of historical documents has recently been recognized by various authors from different fields such as landscape management [5], landscape reconstruction, ecology or forestry [21] and GIS [3, 24].

The objects, in particular natural objects, and their delineations represented in such historical documents usually contain uncertainty to a high degree. This can be referred to as *inherent uncertainty* [24] or *production-oriented uncertainty* [19]. This type of uncertainty is complex and contains different concepts, such as *vagueness*, *ambiguity* and *error*. Different perspectives have contributed to these concepts such as philosophy [28], information theory [18], remote sensing [12], and GIS [10, 31].

Inherent uncertainty manifests itself in a spatial deviation from reality for whatever reason. Often in historical maps only this pattern of deviation can be assessed without any additional knowledge. This is due to the fact that detailed historical background information for thematic interpretation is hardly accessible. One way to assess the accuracy of a map with regard to a reference map is to carry out a quantitative map comparison. Thereby traditional techniques of accuracy assessment using error or confusion matrices produce statistical accuracy measures. There is an abundance of literature describing these techniques in detail [8, 11, 26], for a review in land cover classification). Recently these approaches were extended to assess area estimates from generalized confusion matrices [20] or to derive local summary statistics for geo-statistical analysis [4]. Furthermore combinations of confusion matrix approaches and fuzzy set operations [16, 17, 30] were shown to be flexible methods for map comparison if spatial entities have vague definitions or multi-memberships.

The above mentioned techniques allow the evaluation of map accuracies in general. But the spatial distribution of accuracies can only be considered within an area for which a reference map exists. Such combined methods provide no detailed knowledge of the uncertainty distribution over larger areas, which are not entirely covered by the reference map. In many cases the amount of *inherent* uncertainty varies greatly throughout the considered area depending on local conditions [25]. For the incorporation of historical maps into land cover change assessments, such knowledge would greatly improve the evaluation process. It would support the informed interpretation of the historically mapped objects. To enable this, the knowledge of the *inherent uncertainty* and its variation in space needs to be extrapolated to the whole historical map. This knowledge can be derived from a limited number of local reference maps. Conceptually, this can be done if rules or models can be developed, which link the local uncertainty to a set of generally available predictors. These linkages can be extrapolated into space or to areas not covered by the reference maps.

We present the development of a predictive model for mapping the *inherent* uncertainty of the forest cover of a historical national topographic map of Switzerland originating from the 19th century. These maps were surveyed in extensive field campaigns. Thus we hypothesize that the errors of such mapping efforts can be related to a set of topography-dependent predictors. These are slope, aspect, elevation, as well as distance and visibility from old road networks. The chosen explanatory variables represent factors that are assumed to have been limiting factors for field based surveys, such as visibility or accessibility. By doing so, we aim at finding more general rules, which best describe the quality and the associated errors of topographic field mapping during the 19^{th} century.We use Generalized Linear Models (GLMs) and moving windows to explain the uncertainty found at moving window positions from a set of terrain-derived variables.

GLMs are mathematical extensions of ordinary least-square regression models that do not force data into unnatural scales. Thereby they allow for non-linearity and non-constant variances [22]. This is an important prerequisite, since our dependent variables rate the amount of error in a moving window at a scale ranging from 0 (=perfect fit) to 1 (no agreement at all). Thus the dependent variable is bounded, and cannot easily be treated with ordinary least-square regression. GLMs specifically address this problem and represent thus a suitable approach for our study. These statistical methods are successfully applied to different fields such as predictive habitat modeling in ecology [2, 14, 15], or forest inventories based on remote sensing [23].

2 Materials and Methods

2.1 Study Area and Historical Maps

The historical Swiss National topographic map evaluated here is the first edition of the so-called Siegfried map series. It was published between 1870 and 1920 at scales of 1:25,000 for the Swiss Plateau and 1:50,000 for the mountain regions. As a new feature compared to earlier maps the forest cover was delineated during the field survey. Thus this map is the only source representing forest cover throughout the entire area of Switzerland at this time.

Our study area is the community of Pontresina (Canton Grisons), which is located in an interior valley of the eastern Swiss Alps (Figure 1). As reference data were scarce, the choice of the area was limited. We found only a few areas for which reference data exist. The available reference map for the community of Pontresina belongs to a map series that preceded the official cadastral mapping in Switzerland at that time. They were now mapped as community maps, produced at a scale of 1:5,000 or 1:10,000 with a high degree of detail. These plans are the most reliable spatial representations of landscape objects for the time considered and the instructions for data survey were much more detailed (including forest). Thus we used the forest cover of these maps as a reference to test against the forest cover information of the Siegfried map. Yet there may be an unknown disagreement in the thematic meaning of *forest* leading to a certain spatial effect of uncertainty. In order to exclude additional sources of error, we chose community maps where the date of publication or production did not differ more than 5 years from those of the Siegfried maps.

Both maps were scanned and geo-referenced on the basis of the present-day Swiss national topographic map. Local distortions made the correct registration of the Siegfried map rather difficult. The resulting RMSE using the affine transformation procedure for geo-rectifying was 9.2m. The forest cover was extracted from both datasets to be treated in vector or raster format. The spatial resolution of the raster form of the maps was 1.25m.

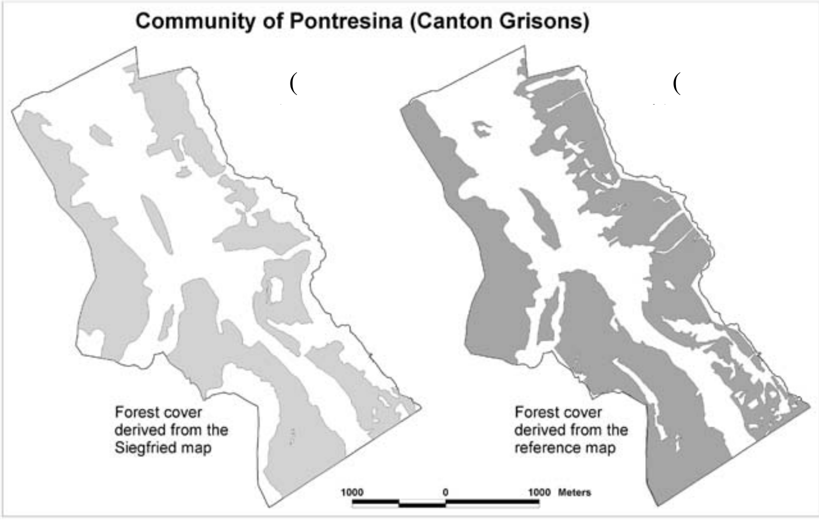


Fig. 1. The forest cover information from (b) the local community map of the study area (Pontresina) was used as a reference for map comparison with (a) the forest cover from the Siegfried map

2.2 Uncertainty Measures: The Dependent Variables

We first derived global measures, such as *percent correctly classified* (PCC) and the *Kappa coefficient* (κ) (based on [11]), from the confusion matrix by pixel-wise comparisons. To examine whether there are trends of uncertainty in relation to topographic gradients, such as slope or elevation, we derived the same measures within different strata (i.e., classes of slope). We found that uncertainty increased along these gradients, which indicated an existing relationship. The measures had to be weighted by the proportion of forest boundary per forest area unit within each stratum since uncertainty became apparent along these lines. This was necessary, because in strata where uncertainty was increasing, larger forest patches (with smaller proportions of forest boundary) occurred.

We had two options to generate a spatially distributed measure of uncertainty: (1) a pixel by pixel evaluation resulting in binary codes of 0 (both maps agree), or 1 (the two maps disagree in representing forest/non-forest), and (2) an aggregated evaluation indicating the degree of uncertainty within a moving window as illustrated in figure 2 (with continuous values between 0 to 1). We decided to use the second approach. Thus we calculated PCC and κ within rectangular moving windows of four different dimensions: 30x30m, 60x60m, 100x100m, and 180x180m. Uncertainty was then defined as 1-PCC and 1-κ. By this, the locally generated statistics provide gradual measures of local disagreement between the two maps (Figure 2).

This allowed us to test the power of variables expressing the topographic configuration in explaining the degrees of uncertainty and to test how the explanatory power varies with spatial aggregation.

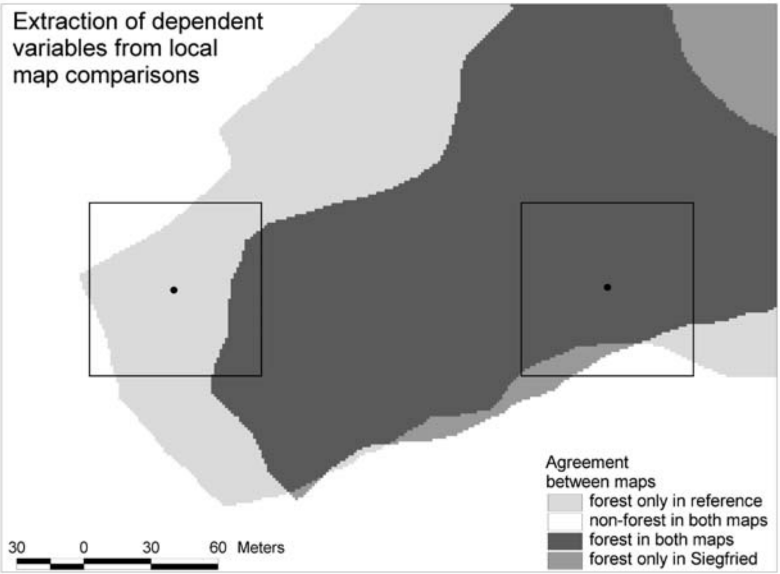


Fig. 2. The dependent variables were locally extracted from pixel-wise map comparisons within moving windows

The equations we used to derive PCC and κ from a confusion matrix of q classes occurring in both the Siegfried and the reference maps have the forms (Eqn. 1 and 2):

$$PCC = P_C = \sum_{i=1}^{q} p_{ii} \tag{1}$$

and

$$\kappa = \frac{P_c - P_e}{1 - P_e} = \frac{P_c - \sum_{i=1}^{q} p_{i+}p_{+i}}{1 - \sum_{i=1}^{q} p_{i+}p_{+i}}, \tag{2}$$

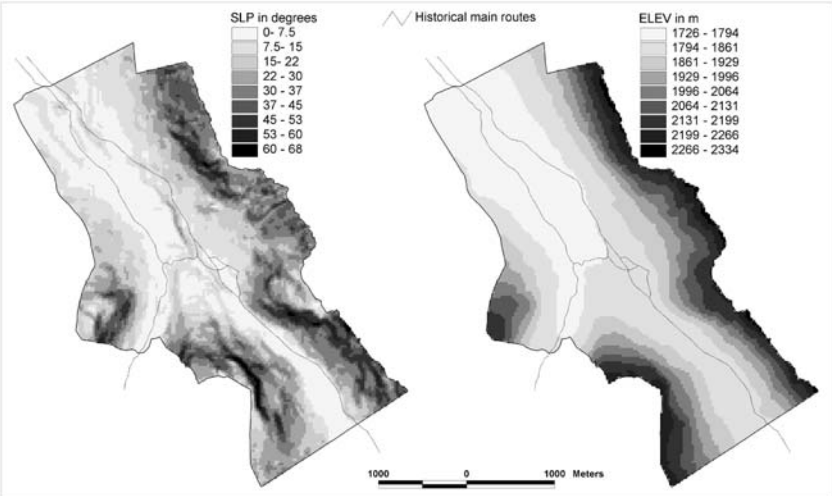
with $$p_{i+} = \sum_{k=1}^{q} p_{ik} \qquad p_{+i} = \sum_{k=1}^{q} p_{ki},$$

where q is the number of classes considered for map comparison, p_{ii} is the proportion of class i that is correctly classified, P_e is the expected proportion of agreement due to chance, p_{i+} is the marginal proportion of row i and p_{+i} is the marginal proportion of column i of the confusion matrix.

In order to prevent pseudo-replication and to reduce spatial autocorrelation, we sampled the grids of the dependent variables at regular distances of at least the length of the moving window. The mesh distances of the sample locations and the resulting sample sizes, which were considerably reduced with increasing window size, were: 30m (9946 points), 60m (2481 points), 100m (1109 points) and 180m (277 points) (Table 2).

2.3 Independent Variables from Topographic Conditions

In order to find explanatory variables for the prediction of the occurrence of uncertainty in field-mapped forest cover the situation of topographic field survey more than 100 years ago has to be considered. Those conditions that had a strong influence on the quality of mapping will represent the variables with the highest explanatory potential. We included topographic conditions such as elevation (ELEV) (Figure 3b) and elevation difference from the lowest point within the study area (ELEVD) from the 25m DEM of Switzerland and its derivatives slope (SLP) (Figure 3a) and aspect (ASP).



(a) (b)

Fig. 3. The independent variables were extracted from topographic gradients such as (a) SLP or (b) ELEV and distances to routes or forest boundaries

In order to link the pixel values to the moving windows analyzed, we calculated the standard deviation of these variables within each window position using focal functions of the ArcGrid module. Thus we obtained measures of variability for elevation (ELEVCH), slope (SLPCH) and aspect (ASPCH). A next variable derived was the "pathdistance" from any location to the closest main route (STRD), which was accessible with the required equipment. We hypothesize that the distance of locations along a historical road to the considered location contains high predictive potential. We also included a measure of visibility of a location (VIS) from the positions of the main routes. Further, we derived the distance from any location in the study area to the closest forest boundary of the reference map (FORD(ref)). This variable is assumed to hold predictive power since it indicates the distance to the main source of uncertainty or, in other words, to the location where spatial patterns of uncertainty can be assessed. Since this variable is only available in the test area, the resulting model is rather an *analytical* model. We derived this measure also from the Siegfried map (FORD) in order to enable a *predictive* model for other areas. We expect that the latter will result in slightly lower model accuracies. All topographic information was derived at a resolution of 25m. A summary of all independent variables used is given in table 1. The four sets of sample points of the dependent variable were intersected with each explanatory variable in a GIS.

Table 1. Description of the independent variables used in the analytical and predictive uncertainty model

Variable	Description
ELEV	Elevation from DEM 25
ELEVCH	Standard deviation of elevation within moving window
SLP	Slope (degree) as derivative of the DEM
SLPCH	Standard deviation of slope (degree) within moving window
ASPCH	Standard deviation of aspect (degree) in moving window
STRD	Pathdistance from moving window center to nearest road
VIS	Visibility of locations from street positions
ELEVD	Elevation difference between moving window center and lowest location
FORD	Distance from moving window center to nearest forest boundary in Siegfried
FORD(ref)	Distance from moving window center to nearest forest boundary in the reference map

With the explanatory variables listed in table 1, we intended to reflect factors that may have influenced the generation of uncertainty during the historical field survey. The main routes within accessible zones such as valleys with flat terrain are assumed to be the locations the topographer passed during the survey. With increasing horizontal and vertical difference, with increasing slope and with changes of aspect from these main routes the uncertainty in mapping the landscape objects (including forest cover) is expected to grow considerably. Reasons are the limited accessibility, the reduced visibility and consequently the increased difficulty in identifying landscape objects (e.g., forest borders). These were due to the conditions of field work at the time: limited transportation capabilities and heavy equipment. Examination of the distance from the closest forest boundary (FORD) showed that locations close to the boundary carry a much higher probability of *inherent* uncertainty than those further away. This measure is expected to have significant predictive power. This is due to the fact that visibility and other terrain features mentioned are not relevant if there is no forest at all or if the location is within a very large forest patch, far away from any boundary.

We do not know from which position the cartographers worked, and many cartographers possibly used different mapping approaches. Therefore, we assume that the resulting predictive model retains a significant unexplained variation of the mapped uncertainties. The remaining variation may include several additional aspects. Apart from others these are weather conditions, seasonal differences, subjective preferences and interests of the topographer and his expertise. Furthermore, the quality of the manual map transcription and reproduction may be responsible for unexplained variation.

2.4 The Statistical Model

In the following we present the formulation of the generalized linear model. The predictor variables X_j *(j=1, ..., p)* are combined to produce a linear predictor (*LP*), which is related to the expected mean value ($\mu = E(Y)$) of the response variable *Y* through a link function *g()*:

$$g(E(Y)) = LP = \alpha + X^T\beta \ , \tag{3}$$

where α is a constant called the regression intercept, *X* represents a vector of *p* predictor variables ($X_1,\ldots,X_p$) of any possible power *T*, and β denotes a vector of *p* regression coefficients ($\beta_1,\ldots,\beta_p$) which are determined for each predictor.

Prior to selecting an appropriate model, the empirical probability distribution of the response variable has to be tested and compared to the theoretical distribution. Our dependent variable follows a binomial distribution since the original measures were given in presence/absence terms of errors from a pixel-by-pixel evaluation. With increasing window size these measures are increasingly weighted due to their local environment and will be included as weighted response variables in the model.

The link function we thus used was the logistic link often termed logit regression model [22]. This link can be described as:

$$g(E(Y)) = \log(\mu/(1-\mu)) \ , \tag{4}$$

which is the logarithm of odds, a model widely used for binomial data [7]. In GLMs the linear combination of predictive or explanatory variables is related to the mean of the response variable through this link function to transform them to linearity and to maintain the prediction values within the range of coherent values for the response [15]. Thus the general logistic regression model we used has the form:

$$\text{logit} = \log(\mu/(1-\mu)) = \alpha + X^T\beta \ . \tag{5}$$

We included linear terms as well as quadratic powers and interactions of the explanatory variables. A maximum-likelihood (ML) estimator is used for fitting the model. We plotted the standardized residuals against the fitted values to identify unexpected patterns in the deviance. All calculations were performed using Splus.

We first fitted a full model, using all explanatory variables (linear and quadratic terms and interactions), then we applied stepwise regression–allowing for both backward and forward selection–in order to optimize the final model. For the analysis of the significance of eliminating or adding terms, the Akaike information criterion (AIC) was used. Thereby, given a fitted model object, individual terms of the model are removed and the respective effect is assessed in comparison to the previous model where the aim is to minimize the AIC [14].

We used χ^2 approximations [22] and AIC measures to test the deviance reduction associated with each variable for significance at a given confidence level (0.05). In addition we tested whether the model coefficients differ significantly from zero using the standard error associated with the estimated model coefficients for a Student t-test. We used the D^2 value (percent deviance explained) to evaluate the model fit, calculated as (*Null.Deviance* – *Residual.Deviance*) / *Null.Deviance*, where the *Null.Deviance* is the deviance of the model with the intercept only, and the *Residual.Deviance* is the deviance that remains unexplained after all final variables have been included. This is equivalent to the R^2 of a linear least-squares regression model. In addition we used the *adjusted* D^2 (derived from *adjusted* R^2 [29]) to take into account the number of observations (n) used for fitting the model and the number of explanatory variables (p):

$$D^2_{\mathrm{adj.}} = 1-\left((n-1)/(n-p)\right)\times\left(1-D^2\right). \tag{6}$$

To produce an uncertainty distribution map the fitted model has to be cartographically represented. For implementation of the model in GIS the inverse of the link function has to be applied to transform the values back to the scale of the original response variable. In our case the inverse logistic transformation is required, which has the form:

$$p(y) = \exp(LP)/\left(1+\exp(LP)\right), \tag{7}$$

where *LP* is the linear predictor fitted by logistic regression (Eq. 4). In applying this retransformation we obtained values between 0 and 1, which is the same as the original response values. This inverse relationship has bias, which can be corrected by using a Taylor series approximation. However, this correction is rarely done in environmental applications. In cases where the mean of the estimated variable is within the range which can be considered fairly linear after transformation (between 0.2 and 0.8) the bias is expected to be very low. Nevertheless, the bias correction has to be done if this condition is not fulfilled.

In order to test the predictive power of the models we split the data set into two parts following the split-sample approach [27]. One part (50%) was used for calibration (training data), the other one (50%) to evaluate the model predictions and to measure the adequacy of the model (test data). Goodness-of-fit measures can then be used to evaluate the fit between the predictions and observations of the evaluation data set. We calculated the non-parametric rank correlation coefficient of Spearman (ρ Rho) and tested it for significance. Furthermore the G-value [1] was used to test the relative improvement of the model over a null model (i.e., the mean of the dependent variable within the calibration data subset).

First, we developed *analytical* models for PCC- and κ-based uncertainty in which the variable FORD(ref) was included as an independent variable in order to examine its explanatory power. Next, we calibrated *predictive* models applicable to areas other than the test site. Thus we replaced FORD(ref) by FORD for both PCC- and κ –based *predictive* models. All models were developed from split-sample data sets.

3 Results

In our study area, the *analytical* models from the 100m windows best describe the relationship between *inherent* uncertainty and the explanatory variables (Figure 4) when compared with the test data. At smaller window sizes, we did not find equally good explanations from the predictors. The model based on the 160m window data set is also inferior (see Table 2 for a comparison of the results). We therefore only present detailed results for the *predictive* models for this 100m window data set, comparing these models with the *analytical* models, respectively.

Table 2. Comparison of PCC-based predictive models calibrated from different window sizes

Window size for PCC extraction	pixel-wise	30m	60m	100m	180m
mean PCC	0.78	0.78	0.78	0.78	0.78
Sample size	9946	9946	2481	1109	277
Goodness of fit: D^2 (if model is significant)	0.16	0.21	0.25	0.31	0.29

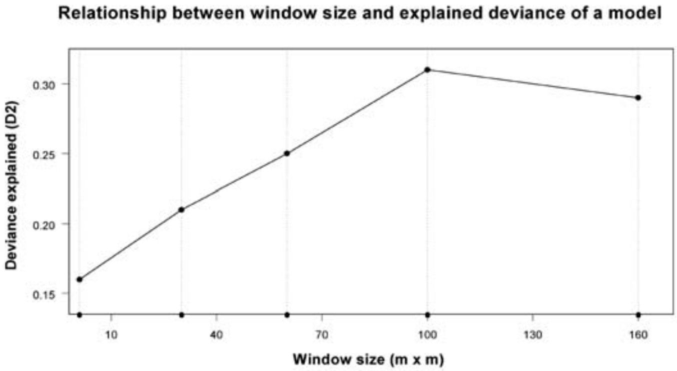


Fig. 4. Relationship between moving window size and deviance explained (D^2) by the fitted model (example for PCC-based models); models were optimized for 100m windows

The *analytical* models for the 100m window (Table 3) indicated significant explanatory power for the uncertainty measures. The step-wise regression resulted in a total deviance reduction of 41 percent for PCC and 46 percent for κ (Table 3, D^2 and *adjusted* D^2). The following variables contributed to the explanation of the fractions of uncertainty in the presented examples: FORD(ref), SLPCH, STRD for PCC-based uncertainty and FORD(ref), SLPCH, ELEVCH, ELEVD and STRD for κ-based uncertainty. When compared with the test data, we received a high agreement for predicted uncertainty (PCC: ρ=0.76, κ: ρ=0.77) within the test site, and the G-values indicated significant improvements over the null model (PCC: G=37%, κ: G=47%, Table 3). Due to the use of distance to the reference forest boundary the results are not applicable to areas outside of the study area.

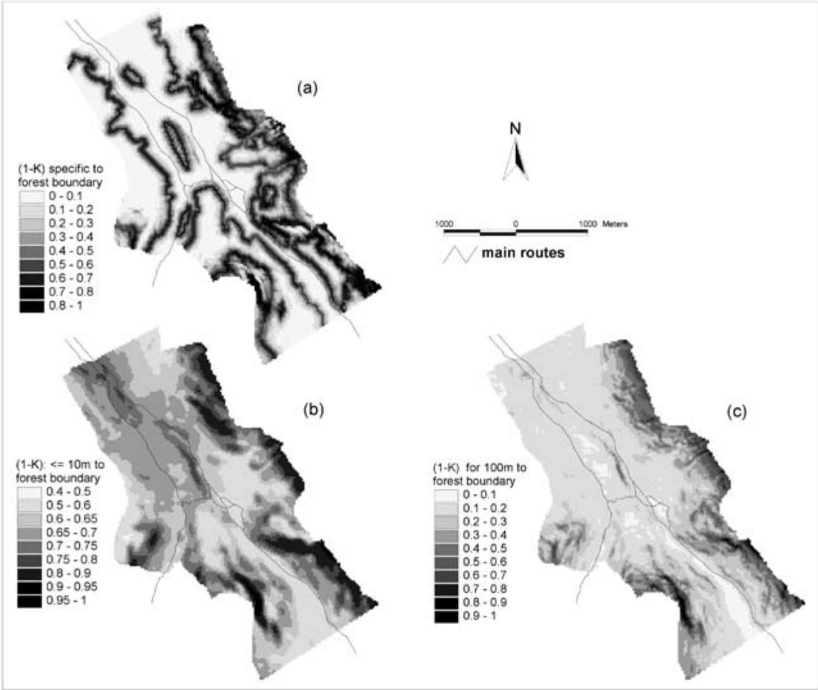


Fig. 5. Predictive uncertainty model for 1-κ as response: (a) site-specific uncertainty, with FORD as predictor, (b) uncertainty predictions with assumed constant values of FORD of 10m, and (c) the same as (b) but for FORD=100m

The calibration of a *predictive* PCC-based model resulted in a slight decrease in model qualities (D^2=0.35, *adjusted* D^2=0.34) and model accuracies (*ρ, G)* when compared to the left-out 554 points. Even though the FORD variable was assumed to be of significantly lower predictive power than the FORD(ref) variable, the *predictive* model still shows similar trends and accuracies (ρ=0.71, and G=0.27). The results of the PCC- *predictive* uncertainty model are presented in Table 3. The following variables contributed significantly to this model: FORD, ELEVD, ELEVCH, SLPCH and STRD.

The κ–based *predictive* uncertainty model revealed a much better model quality D^2=0.41, *adjusted* D^2=0.40), and the model accuracy is almost comparable to the κ-based *analytical* model. Testing the model using the test data resulted in comparably high ρ and G values (ρ=0.75, G=0.47, see Table 3 for an overview). The variables with significant contribution in this case were: FORD, ELEVD, SLP and SLPCH.

Table 3. Results of uncertainty modeling; the *analytical* models (M(pcc(ref)) and M(kap(ref))) and the *predictive* models (M(pcc) and M(kap)) were calibrated on 555 points using uncertainty from 100x100m moving windows, and evaluated on the second subset of 554 points

	Analytical model M(pcc(ref))	Predictive model M(pcc)	Analytical model M(kap(ref))	Predictive model M(kap)
Model quality				
D^2	0.41	0.35	0.46	0.41
Adjusted D^2	0.41	0.34	0.46	0.40
AIC	1359.1	1136.2	1595.9	1442.7
Model test				
Spearman's rank correlation ρ	0.76	0.71	0.77	0.76
G-value	0.37	0.27	0.47	0.47
Model parameters				
Constant	-4.884E-01	-6.210E-01	2.590E-01	8.749E+01
FORD(ref)	-3.368E-02	-	-3.881E-02	-
$(\text{FORD(ref)})^2$	-	-	1.977E-05	-
FORD	-	-1.996E-02	-	-3.157E-02
$(\text{FORD})^2$	-	2.476E-05	-	2.948E-05
ELEVD	-	-3.890E-03	-7.253E-03	-9.375E-03
$(\text{ELEVD})^2$	-	1.150E-05	-	1.521E-05
ELEVCH	-	9.262E-03	-	-
SLP	-	-	-	2.985E-02
SLPCH	1.694E-02	4.195E-03	1.776E-01	8.452E-02
STRD	3.446E-04	6.244E-04	3.715E-03	-
FORD(ref) : SLPCH	1.539E-03	-	-	-
FORD(ref) : ELEVD	-	-	5.974E-05	-
FORD(ref) : STRD	2.373E-05	-	-	-
FORD : SLPCH	-	8.292E-04	-	-
FORD : ELEVD	-	-	-	3.361E-05
ELEVCH : STRD	-	-	-1.295E-04	-
ELEVCH : ELEVD	-	-	2.925E-04	-
SLPCH : STRD	-	-	-1.974E-04	-

As expected, FORD was associated with the most significant deviance reduction in all cases. ELEVD and STRD were highly correlated, which occasionally resulted in a rather random mutual exclusion of one of the two. The same selection behavior was observed for ELEVCH and SLP in all models, since they naturally reflect similar topographic features. ASPFOC and VIS were excluded from all calibration processes since they did not contribute significantly to deviance reduction.

Figure 5 shows the spatial predictions of κ-based uncertainty models. In Figure 5a, we included FORD as predictor. Thus the map represents the spatial uncertainty inherent to this particular map explained by a range of topographic predictors. It is apparent that certain forest boundary zones show less uncertainty than others. In Figures 5b and 5c, predictions are displayed with assumed constant values of FORD (10m and 100m, respectively). By this, the predictions reveal the nature of the modifying effect of the terrain on the forest boundary as mapped in the 19th century and its associated *inherent* uncertainty.

4 Discussion

Overall, the four models calibrated from the 100m sample raster all resulted in models capable of explaining spatial pattern in uncertainty *inherent* in historical and other field based maps. We noticed that the κ-based uncertainty model proved superior both in quality and accuracy when compared to the PCC-based model. This is in agreement with recent research based on confusion matrix evaluations. PCC overestimates the agreement between maps in not accounting for chance agreement [6]. The Kappa coefficient measures the improvement of the *proportion correctly classified* over mere chance agreement [6]. However, κ fails to do so if one class far exceeds the others [9]. PCC showed higher overall agreement across the maps (mean of PCC=0.77) than did κ (mean of κ =0.62). This reflects the over-optimistic map accuracies, thus resulting in generally lower uncertainties and less well spread values across the scale from 0 to 1, compared to κ. This combination of drawbacks for PCC may have caused the difference between the two models.

The inclusion of VIS and ASPCH as explanatory variables did not provide any valuable contribution. The assumptions behind and the extraction processes need to be further tested. All other variables contributed significantly to the models. ELEV and STRD showed comparably high correlations, which is due to the fact that streets climb along the valley. The inclusion of FORD as predictor constrained the uncertainty to the source of error (i.e., the presence of forest boundary, irrespective of terrain features). Figure 5 demonstrates that SLP and SLPCH had high explanatory power since the predicted uncertainty distribution shows a trend along the slope gradient (compare with Figure 3).

We observed single prediction values that clearly deviated from the observed uncertainty in the evaluation subset. This is mainly caused by the many unknown historical factors which resulted in mapping uncertainty. A surveyor may occasionally have added unexpected detail or neglected easy to observe features. Thus, our model only captures the general trends of uncertainty as influenced by topographic features. Despite the rather general approach, the results provide useful insights into the historical mapping process and represent valuable evaluation support for modern use of historical maps. The choice of using window-based summary statistics proved to reflect the disagreement between both maps better than the pixel-wise global comparison. This was the result of changing the window size to optimize the predictive power of the model. One important reason for this may be that windows of 100m are less affected by (sub-pixel) geo-referencing errors. Additionally, the effects of the terrain upon accuracy seem to only be visible at a minimal area considered.

5 Conclusions

When developing the models, we aimed for simplicity and generality. We are aware that, by using additional variables, the model could have been fitted with higher accuracies within the study area. However, such models would be less easily applicable to other areas covered by the Siegfried map. From testing the model against independent data we conclude that the model is applicable to areas of similar topographic nature. Preliminary map comparisons within non-mountainous regions, such as the Swiss Plateau, indicated much higher accuracies, which is what we expect from the fitted models in mountainous terrain. Still, it remains to be tested, how well the existing models perform in non-mountainous terrain.

Historical maps contain valuable landscape information. However, there is an unknown uncertainty inherent in them. To date, only few attempts were made to analyze this uncertainty [21, 24]. In order to make informed use of such documents for land use or land cover change assessment or modeling, it is mandatory, though, to know the quality and inherent uncertainty of these historical data sources. In this paper we have developed a method to predictively map such inherent uncertainty in space.

This method can be applied to any map developed from field surveys under challenging conditions. The topography-related explanatory model variables showed satisfying predictions when the window size was optimized. The spatial predictions of *inherent* uncertainty can thus be used for the evaluation of historical data within different regions by defining fuzzy membership functions and expressing the "possibility of uncertainty" at any given location. Thus the method we presented is very well suited for incorporation into subsequent applications in a larger context to increase the objectivity of the research. We conclude that GLMs represent a very flexible tool for a range of applications. It remains to be tested, whether additional explanatory variables have the potential to improve such models, or if different uncertainty measures such as the NMI [13] are easier to be modeled spatially.

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Paper IV

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Improving land change detection based on uncertain survey maps using Fuzzy Sets

Revised Version submitted to Landscape Ecology

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Abstract

In this paper we present a method for correcting inherent classification bias in historical survey maps with which subsequent land cover change analysis can be improved. We linked generalized linear modelling techniques for spatial uncertainty prediction to fuzzy set based operations. The predicted uncertainty information was used to compute fuzzy memberships of forest and non-forest classes at each location. These memberships were used to reclassify the original map based on decision rules, which take into consideration the differences in identification probability during the historical mapping. Since the forest area was underestimated in the original mapping, the process allows to correct this bias by favouring forest, especially where uncertainty was high.

The analyses were performed in a cross-wise manner between two study areas in order to examine whether the bias correction algorithm would still hold in an independent test area. Our approach resulted in a significant improvement of the original map as indicated by an increase of the Normalized Mutual Information from 0.26 and 0.36 to 0.38 and 0.45 for the cross-wise test against reference maps in Pontresina and St. Moritz, respectively. Consequently subsequent land cover change assessments could be considerably improved by reducing the deviations from a reference change by almost 50 percent.

We concluded that the use of logistic regression techniques for uncertainty modelling based on topographic gradients and fuzzy set operations are useful tools for predictively reducing uncertainty in maps and land cover change models. The procedure allows to get more reliable area estimates of crisp classes and it improves the computation of the fuzzy areas of classes. The approach has limitations when the original map shows high initial accuracy.

Keywords: Predictive uncertainty modelling, fuzzy sets, land cover change analysis, classification bias, correction of survey maps, area estimation

1 Introduction

The analysis of land use and land cover change plays a key role in modern landscape research and landscape ecology (Baker 1989). Different fields such as landscape ecology, geographical information science and remote sensing have contributed considerably to this area (Lu et al. 2004; Coppin et al. 2004). Usually, the length of a considered analysis period is limited to the time span for which aerial photography is available. To consider longer time periods, historical maps can be used (Kienast 1993). Comparing these maps with contemporary maps requires an extensive evaluation since they usually contain considerable inherent uncertainty (Plewe 2002; Leyk et al. 2005). We found few attempts to investigate this uncertainty. Only recently, Leyk and Zimmermann (2004) presented a method for predictive uncertainty modelling in field-based survey maps. With this approach a spatial effect due to inherent uncertainty can be predicted and mapped in relation to hypothesised topographic predictors relevant to historic surveyors. Thus with increasing distance from the valley floor, with decreasing distance to boundaries and with increasing altitude and steepness the mapping quality was found to decrease. This is related to the surveyors' difficulties in earlier times to move in mountainous terrain with heavy equipment as well as the reliability of the historical triangulation network. Although it is not possible to assess all aspects of uncertainty, such models allow to evaluate the original map and to improve map-based area estimates and change analyses.

When considering natural objects, which have multiple memberships and vague definitions, approaches of fuzzy set theory have been shown to be adequate techniques for evaluation and processing. There is an abundance of research dealing with fuzzy sets in landscape analyses based on GIS and remote sensing (Burrough 1989; Fisher 2000; Robinson 2003). Fuzzy sets are frequently used for assessing the classification accuracy based on traditional confusion matrix approaches (Gopal and Woodcock 1994; Binaghi et al. 1999; Jäger and Benz 2000). Matsakis et al. (2000) have presented an approach to evaluate fuzzy partitions in the field of satellite image classification using plausibilistic closure. The improvement of land use map comparisons through fuzzy agreement maps and hierarchical fuzzy pattern matching has been demonstrated by Power et al. (2001). Ahlqvist et al. (2003) demonstrated a unified representation of fuzzy and rough geographical data. Cheng et al. (2001) derived the spatial extent of uncertainties of classified objects based on different fuzzy object models.

Additionally, several studies have attempted to improve area estimates from land cover classes using fuzzy sets. Lewis and Brown (2001) used a generalised area-based confusion matrix for exploring the accuracy of area estimates. Their approach cannot be used for uncertainty-related issues since they defined fuzzy memberships of each class from sub-pixel area proportions which are assumed to sum to unity. Woodcock and Gopal (2000) recognised that area estimates from fuzzy values, which define for each location the degree of uncertainty to be correctly classified, exceed unity for small memberships. Here the limitation is that they used a linguistic scale which does not allow to make full use of fuzzy sets. The fundamental idea that the area of fuzzy geographical entities is a function of the alpha cut, has been used by Fonte and Lodwick (2004) to develop advanced fuzzy area operators. One remaining limitation is the difficulty in interpreting such estimates when several classes have memberships of different meanings. Generally, such approaches are designed for areas covered by reference data. In order to use such approaches for other regions they should be connected to predictive modelling tasks and their success should be measurable.

In this paper we present an approach, which overcomes most of these limitations. We aim at demonstrating how predictive models of uncertainty in a historical map of the 19th century can be linked to fuzzy set approaches in order to improve the map accuracy and historical forest area estimations. The combined approach allowed us to remove bias from historical maps, thus increasing the accuracy of land change detection. Fuzzy sets were derived from predicted spatially explicit uncertainty maps. A reclassification procedure is presented, which differentiates identification probabilities of different landscape classes. The analysis was developed within two study areas in the Swiss Alps, which allowed us to evaluate the method in independent test areas.

2 Fuzzy sets and fuzzy classifications

Fuzzy sets

Here, we briefly introduce the main aspects of fuzzy sets and fuzzy classifications assuming some theoretical background, which can be found in Burrough and McDonnell (1998), Dubois and Prade (2000) and Robinson (2003). The concept of fuzzy sets introduced by Zadeh (1965) provides ways of dealing with natural geographic variability and complexity when considering vegetation or land cover classes. A membership function defining the degree of membership of an element to each of the existing classes allows us to address the gradual transition and multi-memberships in space. Thus by using fuzzy sets one can overcome the limitations of crisp sets in which only full or no membership can be assigned to each unit (Klir and Wierman 1999). A formal definition of a fuzzy set can be given as follows: Let $X=\{x\}$ be a finite set or space of geographical entities x of one considered class (universe of discourse). A fuzzy set A of this space is defined by a membership function μ_A in the ordered pairs $A = \{x, \mu_A(x)\}$ for each $x \in X$. The membership values range from zero (no membership) to one (full membership) on a continuous scale and with gradual transition: $\mu_A: X \rightarrow [0,1]$.

There are different approaches to assign membership functions appropriately resulting in linguistic (Power et al. 2001; Woodcock and Gopal 2000), categorical or continuous (Brown 1998; Andréfouët et al. 2000) membership values. Robinson (2003) describes the fundamental concerns of choosing the right membership function as standard function, problem-specific function or from data-driven approaches in GIS-related applications.

Fuzzy classification

Land cover maps often consist of classes that are continuous in nature. Thus many locations are expected to show gradual or multi-memberships to different classes, in particular close to boundaries. To account for these characteristics fuzzy classifications (Foody 1996; Bolliger et al. 2005) or fuzzy partitions (Matsakis et al. 2000) have been applied. They can be obtained by fuzzy classifiers, softening of crisp classes or neural networks (Woodcock and Gopal 2000).

A pixel (x_j) of the universe of discourse X ($X = \{x_j\}_{j = 1,...,N}$) covers more than one land cover class (i) especially when the location is in the transition zone between two classes, which are neither well-defined nor spatially distinct. Therefore, a fuzzy classification is a family of M fuzzy sets $\{\mu_1,\ldots, \mu_M\}$ such that $\forall i = 1,\ldots, M$, $\mu_i \neq \varnothing$, $\mu_i \neq X$ (Dubois and Prade 2000). Given these conditions, a fuzzy partition into M classes of X can be considered as an M-tuple $\mu_{i,\ i = 1,\ldots,M}$ of functions from X into [0,1] such that:

$$\forall j = 1,...,N, \exists i = 1,...,M \setminus \mu_{ij} > 0, \text{ and} \tag{1}$$

$$\forall i = 1,...,M, \exists j = 1,...,N \setminus \mu_{ij} > 0, \tag{2}$$

where μ_{ij} denotes the membership degree of pixel x_j of X in fuzzy class i. N and M denote two integers such that $N \geq M \geq 2$ and X denotes a set of N elements (universe of discourse) as described above. The membership μ_{ij} has been interpreted as possibility that element x_j of X belongs to class i (Krishnapuram and Keller 1993). Adding the condition $\forall j = 1,\ldots,N$, $\sum_{i = 1,\ldots,M} \mu_{ij} = 1$ to Equations (1) and (2), probabilistic fuzzy partitions are obtained (Ruspini 1969; Bezdek 1981). In remote sensing, fuzzy partitions are frequently considered to be probability distributions where membership degrees nearly agree with the land cover proportion inside a considered pixel. Thus they sum to 1. In cases where they do not sum to 1, they cannot be considered probabilistic. In some cases such a partition is treated as possibilistic fuzzy partition (Matsakis et al. 2000).

Area estimation from fuzzy classes

Various authors described the area of a fuzzy class as a function of class membership. In cases where the fuzzy memberships are representing the uncertainty of belonging to a class they cannot be seen as proportion of that class within the pixel as is frequently done in remote sensing (Lewis and Brown 2001). Thus the area of fuzzy class A_i has to be represented as a function of the alpha cut level, which indicates at what level of fuzzy membership a pixel is considered to belong to class i exclusively. Given the condition $\forall i = 1,\ldots,M,\ \exists\ x_j \setminus \mu_{ij} = 1$ which implies that $h(\mu_i)=1$, where h is the height of the fuzzy set (Klir and Wierman 1999), fuzzy class i can be considered as a normal fuzzy set. Thus it can be represented as a group of alpha cuts, for $\alpha \in [0,1]$. The area of a fuzzy object represented by a normal fuzzy set is the sum of the areas of the pixels of this object, which belong to the defined alpha cut level. Thus the areas of pixels j of class i, for which $\mu_{ij} \geq \alpha$, are summed to represent the area of the fuzzy object i as a decreasing left continuous function of the alpha cut level (Fonte and Lodwick 2004). For low alpha cut levels the area of the fuzzy class exceeds the area of a (crisp) reference class (Woodcock and Gopal 2000) resulting in proportions > 1 (Figure 1).

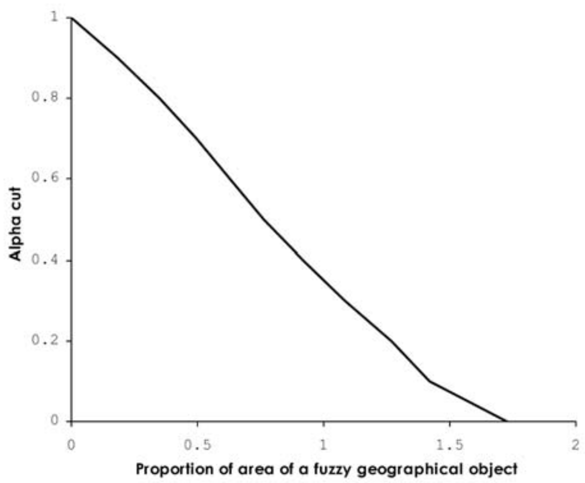

Figure 1. Presentation of the area of a fuzzy geographical entity as a function of the alpha cut.

One problem with this approach is that for different classes i the meanings of their memberships are assumed to be equal. In nature the classes have very different properties and different transition characteristics. To solve this problem, the respective alpha cut levels have to be computed in relation to all classes simultaneously. This is one prerequisite to achieve more reliable area estimates and defuzzification results if two or more classes are involved.

3 Material and methods

In the following, we describe a sequence of steps that were necessary to improve an original crisp forest / non-forest map for more reliable area estimations based on a combination of predictive uncertainty modelling and bias correction using fuzzy set theory (Figure 2). First, the predictive modelling procedure (Leyk and Zimmermann 2004) is presented, which allowed us to predict the spatial effect of uncertainty in mapping forest as a function of topographic features. Then we demonstrate how the modelled uncertainty, which was converted to certainty, was used to transform the original crisp classes into two fuzzy classes, forest and non-forest, respectively, to account for transition zones and gradual memberships.

Finally, we present decision rules for the retransformation of the fuzzy classes into new crisp classes. This step aimed at improving classification accuracy and area estimations by correcting the bias in the mapped forest area, which was expected to be underestimated. The basic idea was that during the historical fieldwork, which was object-driven, different identification probabilities have to be expected for forest and non-forest, respectively. Where "forest" was mapped, we could assume that forest had been found approximately at this position since the topographer had identified this object. Whenever forest could not be identified, the alternative class "non-forest", which was not extensively searched for, was assigned. Consequently, the memberships of forest and non-forest cannot be treated equally, especially in areas of low certainty. To account for this, dynamic weighting factors were examined to find the optimal retransformation, i.e. where the improvement in classification accuracy and thus the correction of bias reached their maximum.

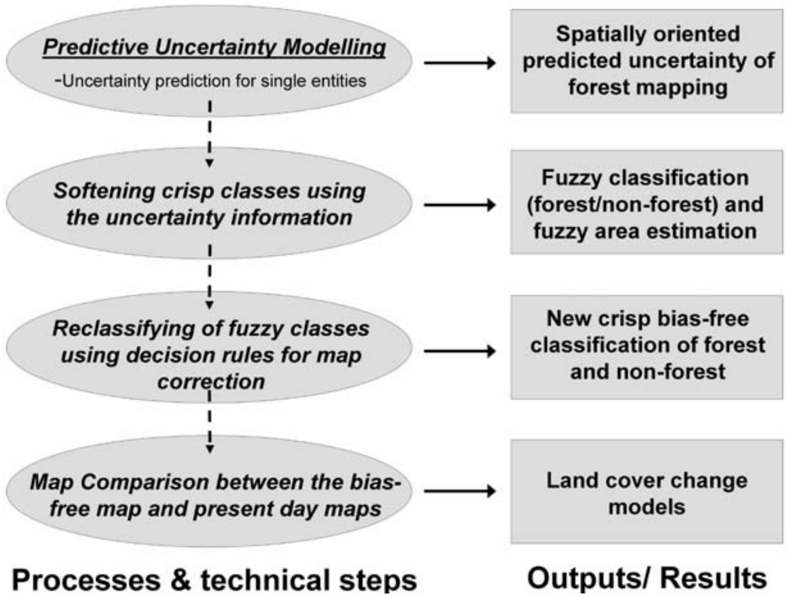

Figure 2. Process flow for improved land change analysis including predictive uncertainty modelling, uncertainty-based fuzzy set generation, rule-based bias correction to produce new reclassified forest/non-forest maps and map comparison with contemporary maps.

3.1 Study area, historical, and modern maps

The historical map to evaluate was the first edition of the so-called Siegfried Map series – the historical Swiss National topographic map published between 1870 and 1920. The special new feature here, compared to earlier maps, was the delineation of the forest cover. This allowed us to derive spatially explicit forest cover information for the entire area of Switzerland for that time period. Our study areas included the municipalities of Pontresina, where the uncertainty model had been developed (Leyk and Zimmermann 2004), and St. Moritz (Canton Grisons) (Figure 3). For both communities we had access to accurate, local reference maps, which are otherwise scarce for the considered time period. This enabled us to cross-wise calibrate and test the uncertainty model, and to assess its robustness and generality. These reference maps – communal maps at a scale of 1:5,000 or 1:10,000 with a high degree of detail – belong to a map series that preceded the official cadastral mapping in Switzerland at that time. For geo-rectification of all maps involved, we chose the projection of the present-day Swiss topographic map. There was evidence of some differences regarding the meaning of forest. We observed that avalanche tracks, larger bedrocks and other gaps within the forest area were rarely mapped as non-forest or represented extremely dislocated in the Siegfried Map. In the reference maps these details were mapped almost completely with high spatial detail.

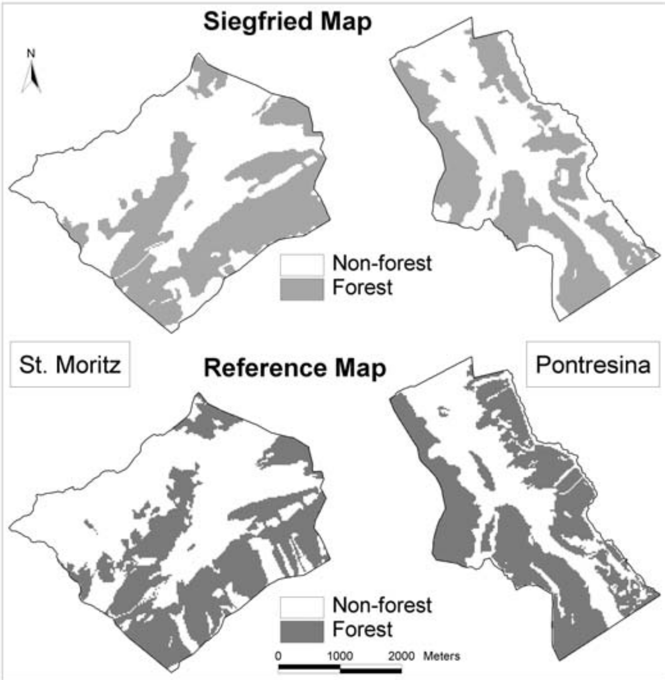

Figure 3. Forest/Non-forest classes derived from Siegfried Map and reference maps of the two study areas Pontresina and St.Moritz.

In an example of an application, we compared the improved historical map with a modern forest / non-forest map, which we derived from the Swiss topographic map at a scale of 1:25’000 (LK25 maps from 2003, © Swisstopo). The map was available in digital form and allowed the distinction of the closed canopy forest layer.

3.2 A regional predictive uncertainty model

In an earlier study we presented a method for predictively modelling the spatial pattern of inherent mapping uncertainty using topographic and distance measures as predictors (Leyk and Zimmermann 2004). The rationale for this approach was to mimic the difficulties of surveyors to identify forest and non-forest for mapping at the time of the Siegfried Map. By applying Generalised Linear Models (GLM) using the logit link function, we were able to incorporate these relationships into a predictive uncertainty model of mapping forest / non-forest classes. The general logistic regression model had the form (Equation (3)):

$$logit = log\left(E/(1-E)\right) = \alpha + X^T\beta\,, \qquad (3)$$

where α is the regression intercept, X represents a vector of p predictor variables ($X_1,\dots,X_p$) of any power T, and β denotes a vector of p regression coefficients ($\beta_1,\dots,\beta_p$) which were determined for each predictor. Finally, E is the expected mean value of the response variable. GLMs perform regressions in a transformed space, overcoming the restrictions of ordinary least-squares models (e.g., E is bounded between 0 and 1).

In our recent study, the independent variables ($X_1,\dots,X_p$) distance to forest boundary (FORD), elevation difference to valley bottom (ELEVD) and slope (SLP) carried highest predictive power for local uncertainty (E) of a target pixel, as the model tests showed. We computed E as 1 – Kappa coefficient of agreement (κ) within local windows of 100x100m. In each window the accuracy of the Siegfried Map was tested against the reference maps and E

was recorded at the central pixel. We distributed the local windows systematically at regular distances larger than the window sizes to avoid overlaps and to reduce spatial autocorrelation and pseudo-replication (Figure 4). The layer of the values $E = 1 - \kappa$ was intersected with the independent variables to calibrate a predictive statistical model using GLMs in Splus (Insightful 2001). The model allowed us to map E in a spatially explicit form, where $E = 0$ indicates a perfect fit and $E = 1$ means no agreement at all.

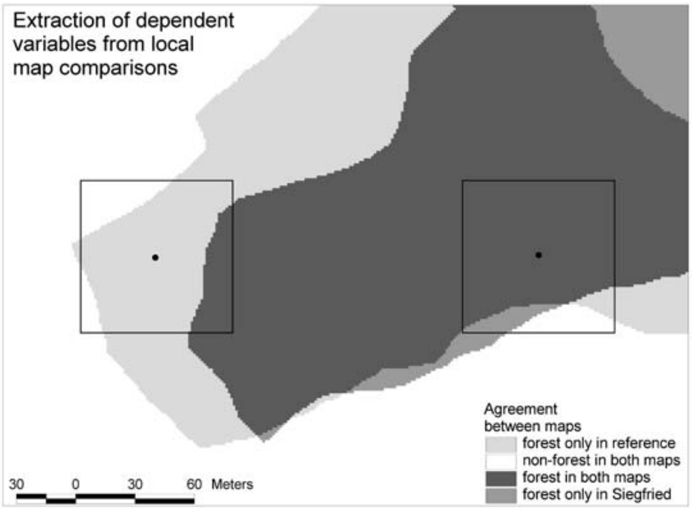

Figure 4. Derivation of the dependent variable for predictive uncertainty modelling. Local summary statistics are derived within local windows distributed throughout the area (from Leyk and Zimmermann 2004).

We applied standard stepwise regression procedures starting from a full model including all predictors in linear and quadratic form, and allowing for both backward and forward selection in order to optimize the models based on the AIC criterion. We reported AIC and the adjusted D^2 values (Guisan and Zimmermann 2000) for the goodness-of-fit of the models and we additionally reported the final model parameters. Independent tests were performed by comparing the model calibrated at the respective other area with E as derived from the comparison with local communal maps. These tests were based on mean absolute error (*MAE*), which is the weighted average of the absolute errors, Spearman's rank correlation ρ, and the *G*-value, which indicates the relative improvement of the model over the null model i.e., the mean of E within the calibration data set. *MAE* ranges between zero (perfect fit) and infinity (no fit at all). The latter two measures report high accuracy if values are close to 1 and random agreement if values are 0.

3.3 Generating fuzzy memberships from spatial effects of uncertainty

The predicted uncertainties were used for defining fuzzy memberships of forest and non-forest by softening the original crisp classification. It is important to note that there is no specific type of uncertainty accounted for. The uncertainty model provides information on the spatial pattern of inherent uncertainty (Leyk et al. 2005), which is quantified by E (Equation (4)). Possible reasons, which cannot be differentiated, are vague definitions, mapping errors or ambiguous concepts. We used the semantic import (SI) (Robinson 1988) approach to assign the fuzzy membership functions. This was done by computing for each pixel j the degree of certainty C_j with $C_j = 1 - E_j$ and importing C_j as external data to relax the original crisp classification of the Siegfried Map CL with $CL = 1$ for forest and $CL = 0$ for non-forest (Figure 5a). Thus the degree of belonging to forest and non-forest and thus multi-memberships was defined by C_j.

The modelled C values at the forest boundaries (C_{bound}) showed local minima tending towards 1 with increasing distance from the boundary (Figure 5d). To derive fuzzy sets for forest (F) and non-forest (NF), C had to be transformed into two one-sided continuous surfaces based on the membership functions μ_F for F and μ_{NF} for NF. The resulting memberships have to be decreasing when moving from the inside of one class towards the inside of the other class, showing multi-memberships within transition zones close to the boundaries. At such transitional positions it was expected that, where $CL = 1$, $C_{bound} \geq \mu_{NF} > 0$ and where $CL = 0$, $C_{bound} \geq \mu_F > 0$, with μ_{NF} and μ_F tending towards zero with increasing distance from the boundary, respectively. To transform C into μ_{NF} where $CL = 1$ and into μ_F where $CL = 0$, the C_{bound} values had to be interpolated into space. The resulting surfaces are B_F, which represents the interpolated C_{bound} values where $CL = 0$, and B_{NF}, which represents the interpolated C_{bound} values where $CL = 1$ (Figures 5b, c). Only pixels whose centres were less than half the size of a pixel away from the digitized boundary line in the Siegfried Map were considered when applying inverse distance weighted interpolation (IDW) with only two neighbours. Thus the values of B_F and B_{NF} were spatially weighted by the distance to all surrounding C_{bound} values.

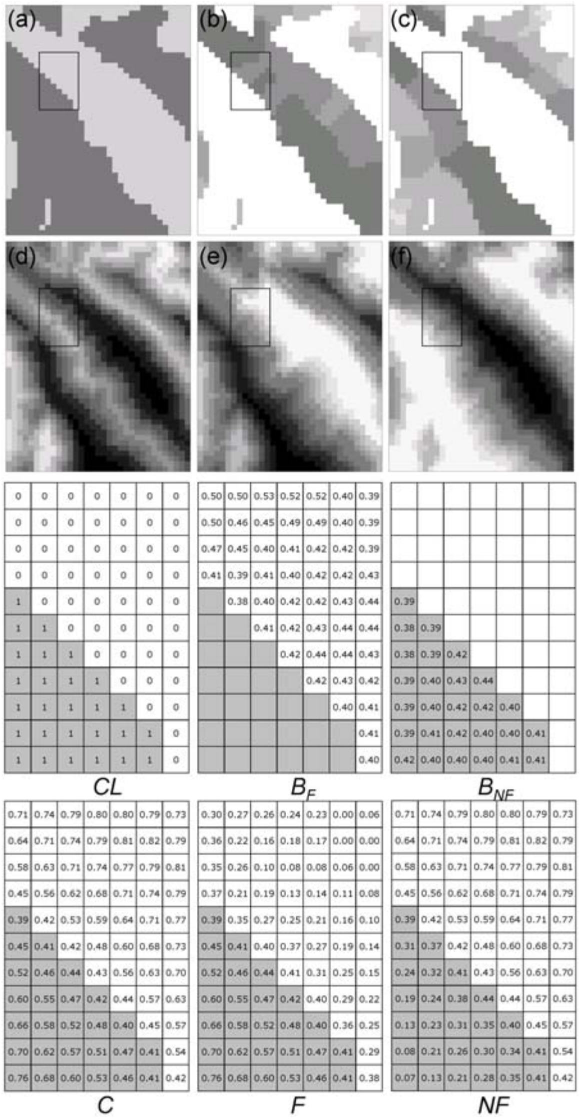

Figure 5. Derivation of fuzzy classes F for forest (e) and NF for non-forest (f) using Equations (4) and (5) using the crisp original Siegfried classification CL (a), the interpolated C_{bound} values B_F (b) and B_{NF} (c) and the certainty values C (d). Below, numeric values from the sub-window in the grey scale images are presented as an example.

The surfaces CL, C, B_F and B_{NF} could now be used to compute μ_F and μ_{NF} for each pixel j: Let $X=\{x_j\}$ be the space of objects of one class covering one study area. The two fuzzy sets F

and NF of X were defined by μ_F and μ_{NF} in the ordered pairs $F = \{x_j, \mu_F(x_j)\}$ and $NF = \{x_j, \mu_{NF}(x_j)\}$, respectively, for each $x_j \in X$, $\mu_F: X \rightarrow [0,1]$, $\mu_{NF}: X \rightarrow [0,1]$. The membership values $\mu_{F,j}$ and $\mu_{NF,j}$ at locations j, $j=1,\ldots,N$, were computed as follows:

$$\mu_{F,j}\left(C_j, B_{F,j}, CL_j\right) = \begin{cases} C_j & \text{if } CL_j = 1 \\ B_{F,j} - \left(C_j - B_{F,j}\right), & \text{if } CL_j = 0 \text{ and if } B_{F,j} > \left(C_j - B_{F,j}\right), \\ 0, & \text{if } CL_j = 0 \text{ and if } B_{F,j} < \left(C_j - B_{F,j}\right) \end{cases} \tag{4}$$

$$\mu_{NF,j}\left(C_j, B_{NF,j}, CL_j\right) = \begin{cases} C_j & \text{if } CL_j = 0 \\ B_{NF,j} - \left(C_j - B_{NF,j}\right), & \text{if } CL_j = 1 \text{ and if } B_{NF,j} > \left(C_j - B_{NF,j}\right), \\ 0, & \text{if } CL_j = 1 \text{ and if } B_{NF,j} < \left(C_j - B_{NF,j}\right) \end{cases} \tag{5}$$

where C_j is the local certainty at location j, derived from $C = 1 - E$ (E is from Equation (3)), $B_{F,j}$ and $B_{NF,j}$ are the interpolated C_{bound} values at locations j, where $CL_j = 0$ and $CL_j = 1$, respectively, and CL_j indicates the Siegfried forest (1)/non-forest (0) classification (Figure 5a). At locations j, where $CL_j = 1$, $\mu_{F,j}$ was defined as $\mu_{F,j} = C_j$ (Equation (4)), where $CL_j = 0$, $\mu_{NF,j}$ was defined as $\mu_{NF,j} = C_j$ (Equation (5)). This is a direct conversion of C_j into memberships.

The assignment of the remaining locations was more complex: At locations j, where $CL_j = 0$, $\mu_{F,j}$ of F was computed as $B_{F,j} - (C_j - B_{F,j})$. Thus $\mu_{F,j}$ decreases with increasing C_j when moving away from the forest boundary within the non-forest area since $B_{F,j}$ only varies to a small degree. Due to resolution effects C_j was slightly smaller than $B_{F,j}$ in some cases close to the boundary. In such cases $\mu_{F,j}$ was defined as $\mu_{F,j} = B_{F,j}$ since $C_{bound,j} \geq B_{F,j}$ can be assumed. Where $C_j > 2 \times B_{Fj}$, $\mu_{F,j}$ becomes negative. Since the increase of C is related to a decrease in μ_F, negative values indicate a forest membership of zero (Equation (4)). This procedure was applied to compute $\mu_{NF,j}$ of NF for locations j, where $CL_j = 1$ (Equation (5)), accordingly. With this approach, which is illustrated in Figure 5 by a matrix of computed values within a subset window, we derived two fuzzy sets, F and NF (Figure 5e, f) on a continuous scale.

3.4 Area bias correction from fuzzy memberships

The fuzzy classification was used in a rule-based reclassification procedure to create a new crisp forest (1)/non-forest (0) map (CL_{Defuzz}) of improved accuracy by correcting bias. This was necessary to compare the historical map with contemporary land use maps for land change analysis. Such a reclassification allowed us to assess the gain in accuracy of the historical maps after bias removal and to compute more reliable area estimates at the same time.

The decision rules have the effect that forest, which is underestimated, is weighted due to the lower identification probability during the historical mapping. For this weighting a new variable THR ($THR \in [0,1]$) is introduced. It represents the threshold value for C to differentiate between pixels j of high certainty ($C_j \geq THR$) and low certainty ($C_j < THR$). Where C was high, such as in valleys or close to roads forest boundaries are trustworthy and expected to be accurately delineated. At these locations μ_F and μ_{NF} could be compared directly to each other. These pixels are assigned to the class "forest" (CL_{Defuzz}=1) where $\mu_{Fj} \geq \mu_{NFj}$ and to "non-forest" (CL_{Defuzz}=0) where $\mu_{Fj} < \mu_{NFj}$. Where C was low, say on steep slopes away from roads, pixels were assigned to CL_{Defuzz}=0 where $\mu_{Fj} = 0$ and to CL_{Defuzz}=1 where $\mu_{Fj} > 0$. Thus forest was enforced at even very low memberships, which is an indication of forest in the historical map in close vicinity. Thus THR defines the degree to which forest is enforced. The decision rules, which are based on μ_F, μ_{NF}, C_j and THR, are presented in Equation (6):

$$CL_{Defuzz,j} = \begin{cases} 1 & \text{if } (C_j \geq THR \text{ and } \mu_{Fj} \geq \mu_{NFj}) \\ 1 & \text{if } (C_j < THR \text{ and } \mu_{Fj} > 0) \\ 0 & \text{if } (C_j \geq THR \text{ and } \mu_{Fj} < \mu_{NF,j}), \\ 0 & \text{if } \mu_{Fj} = 0 \end{cases} \tag{6}$$

where $CL_{Defuzz,j}$ is the value of the new reclassified crisp set CL_{Defuzz} at location *j*. We iteratively computed all possible new crisp classifications for $THR \in [0,1]$ in steps of 0.01 and compared them with the reference maps for assessing the new accuracies. We computed three measures of accuracy: namely, the percentage of correctly classified pixels (PCC), Cohen's Kappa (Cohen 1960), and the Normalized Mutual Information (NMI) (Forbes 1995). The best new classification was found where the gain in accuracy against the reference maps reached its maximum. For this value of *THR* the bias in forest area can be considered corrected. This procedure is flexible since it can be used to find out first, which class (direction) is underestimated (i.e., increasing accuracy of CL_{Defuzz} when enforcing the class) and second, to what degree this class has to be enforced to correct bias. For a validation of the predictive power of the analysis, the optimal values of *THR* had to be similar in both study areas. Such a similarity could indicate the applicability of the approach to new areas of similar topographic characteristics. This has to be validated through an extended analysis.

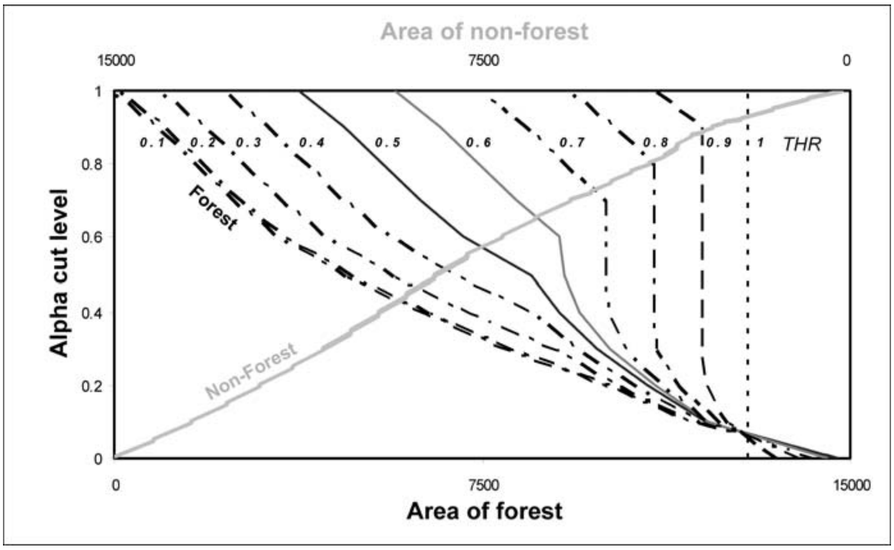

Figure 6. Fuzzy areas (unitary pixels) of non-forest and forest. Non-forest areas, represented by the grey line oriented from the right to the left, are computed as function of the alpha level only. The fuzzy area of forest additionally considers *THR* which runs from 0 to 1, indicated by italic numbers close to the graphs.

If the new map shows higher accuracy, it could be used for more reliable area estimation of the crisp classes, forest and non-forest on the one hand. On the other hand, the above described decision rules can be used to derive the areas of the fuzzy classes, *F* and *NF* based on different identification probabilities. The fuzzy area of *NF* is considered a function of the alpha-cut and was called $Area_{NF}(\alpha)$ (Figure 6). The result was a family of crisp sets, where the areas of all pixels for which $\mu_{NFj} \geq \alpha$ were summed to derive $Area_{NF}(\alpha)$. The fuzzy area of forest was computed as a family of crisp sets, each as a function of two independent variables, *THR* and α and is called $Area_F(THR,\alpha)$. The equations used for computing $Area_{NF}(\alpha)$ and $Area_F(THR,\alpha)$ are given below (Equations (7) and (8)):

$$Area_{NF}(\alpha) = \sum_{j=1}^{n} x_j \,, where \; (\mu_{NFj} \geq \alpha) \,, \tag{7}$$

$$Area_F(THR,\alpha) = \sum_{j=1}^{n} x_j \,, where \; (C_j \geq THR \; and \; \mu_{Fj} \geq \alpha) \; or \; (C_j < THR \; and \; \mu_{Fj} > 0), \tag{8}$$

where x_j are the areas of pixels *j*. In Equation (8) $Area_F$ is computed for all combinations of $THR \in [0,1]$ and $\alpha \in [0,1]$ and presented for *THR*= 0.1 up to *THR*=1 (steps of 0.1) for illustration (Figure 6). For very small values of *THR*, $Area_F$ equals a function of α only. $Area_F$

increases with increasing *THR* and decreasing α. The range of $Area_F$ for $\alpha \in [0,1]$ is determined by the number of pixels fulfilling the conditions $C_j \geq THR$ and $\mu_{Fj} \geq \alpha$, which means that either $C_j = \mu_{Fj}$ if $\alpha \geq THR$ or $C_j \neq \mu_{Fj}$ if $\alpha < THR$. This range decreases with increasing *THR*. The main reason is the increasing proportion of pixels fulfilling the conditions $C_j < THR$ and $\mu_{Fj} > 0$, which corresponds to the correction of forest area in Equation (6). This results in an increase of $Area_F$, independently on α, which is discernable by a shift of the graph to the right with increasing *THR* (Figure 6). Accordingly, the range of $Area_F$ diminishes, which is reflected by steeper sections of the graphs for $\alpha < THR$ below a breakpoint for each *THR* at $\alpha = THR$. These sections tend to be perpendicular for $THR \geq 0.7$ resulting in an entirely perpendicular graph for the extreme $THR = 1$. For very large *THR* overestimations of forest area can thus be expected.

4 Results

Predictive uncertainty modelling and the derivation of fuzzy sets

The models calibrated independently for the two regions indicated reasonable predictive power for uncertainty *E* when tested in the respective other study area. The model calibrated in the St. Moritz area performed slightly better. The step-wise regression resulted in a total deviance reduction of 35 percent in St. Moritz and 31 percent in Pontresina (Table 1, *adjusted* D^2), respectively. When compared with the independent test data, we received a high agreement and acceptable errors for the predicted values *E* (ρ=0.67 and MAE=0.19 when calibrated in St. Moritz and tested in Pontresina; ρ=0.69 and MAE=0.16 when calibrated and tested vice versa). The G-values indicated significant improvements over the null model (*G*=38%, *G*=44%, respectively, Table 1). The regression coefficients of both models have the same signs and are very similar values (Table 1**)** indicating a constant model performance over two test areas of different topographic characteristics. The cartographic representations of the distributions of certainty *C* and the resulting fuzzy sets *F* and *NF* for both study areas are shown in Figure 7.

	Calibration: St.Moritz Testing: Pontresina	Calibration: Pontresina Testing: St.Moritz
Model quality		
D^2	0.35	0.32
Adjusted D^2	0.35	0.31
Cross-wise Model test		
Spearman (ρ)	0.67	0.69
G-value	0.38	0.44
MAE	0.19	0.16
Model parameters		
Constant	3.187E-01	3.073E-01
FORD	1.278E-02	1.400E-02
ELEVD	-2.299E-02	-8.461 E-03
SLP	-1.755E-03	-3.259E-03

Table 1. Results from predictive uncertainty modelling. The models were calibrated in each area, and tested crosswise in the respective other area for independent accuracy assessment.

Bias correction, accuracy assessment and area estimation

Using the decision rules outlined in section 3.4, we corrected the forest area as mapped in the Siegfried Maps using NMI-based optimized thresholds. The new bias-corrected forest/non-forest maps showed higher accuracies than the original Siegfried Maps when tested against the reference maps of the respective other community (Figure 8; Table 2). The gain in accuracy for Pontresina is considerably higher (NMI changes from 0.26 to 0.38) than for St. Moritz (NMI changes from 0.36 to 0.45). Altogether, the proportion of misclassified area could be decreased from 6418 to 4873 pixels compared to the original map. The range of *THR*, for which the gain in classification accuracy reached its maximum in both study areas simultaneously, is between 0.49 and 0.57 (Figure 8). The presented results (Table 2) and the improved maps (Figure 9) were computed based on *THR* = 0.54.

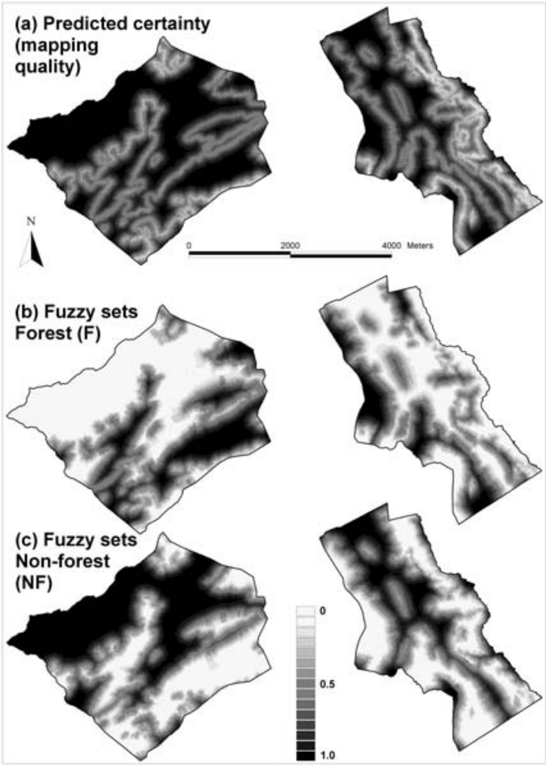

Figure 7. Cartographic certainty distributions as predictive model output (a) and fuzzy sets for forest (b) and non-forest (c) in both study areas, St. Moritz (left) and Pontresina (right).

	Pontresina	**St. Moritz**
Reference map		
Forest area	8350	8223
Non-forest area	6486	11496
Original classification		
Forest area correct	5853	6619
Non-forest area correct	5649	10016
Misclassified proportion	3334	3084
PCC	0.76	0.84
Kappa	0.55	0.67
NMI	0.26	0.36
Improved classification		
Forest area correct	7080	7298
Non-forest area correct	5469	9835
Misclassified proportion	2287	2586
PCC	0.85	0.87
Kappa	0.69	0.74
NMI	0.38	0.45
Optimal THR values	0.49	0.59

Table 2. Improvement of the historical map indicated by global accuracy measures and the decrease of misclassified proportions. The results are computed for THR=0.54.

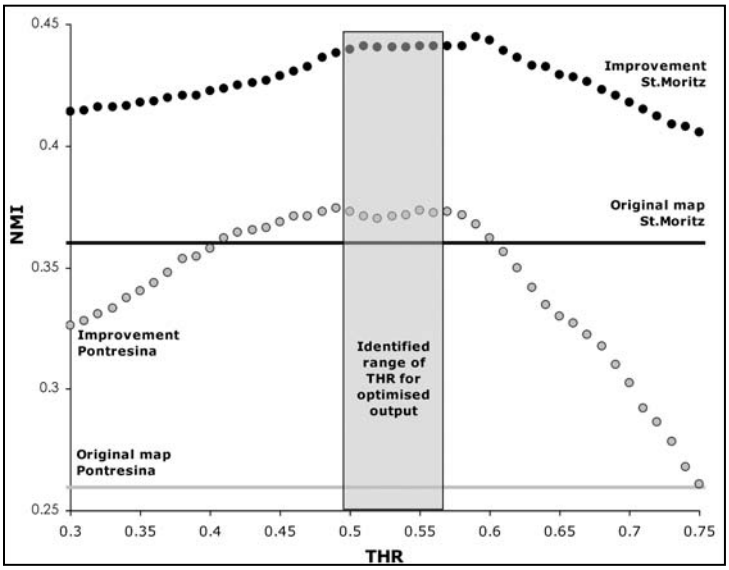

Figure 8. Gain in map accuracy after reclassifying the fuzzy sets compared to the original map accuracy (NMI). The range of *THR* with high improvement is marked by the grey box.

This gain in accuracy of the new crisp map justifies the computation of $Area_F$ and $Area_{NF}$ (Figure 6). Due to the embedded correction, the values of $Area_F$ for $0.49 \leq THR \leq 0.57$ are significantly higher than for *THR* close to zero, which is the same as a function of alpha only.

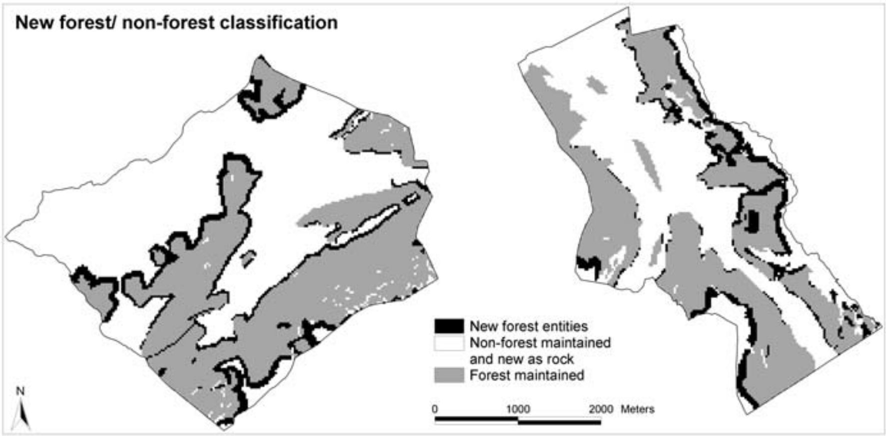

Figure 9. Bias-corrected new crisp maps with the new forest units in black. The initial underestimation of forest area could be corrected, especially in regions of high uncertainty.

An example of a land-cover change analysis

The example of forest cover change analysis was applied to both study areas using the forest cover of the modern map (Table 3). The deviation of the computed changes as measured from the change based on the reference maps could be decreased from 4960 units to 2602 units. Thus the procedure resulted in a reduction of misclassified land cover change units by nearly 50 percent. This improvement becomes especially obvious in the Pontresina study area where this deviation could be decreased from 3048 to 848 units (Table 3). In the St. Moritz study area forest area in the new historical map and thus the estimation of changes from forest to non-forest were slightly overestimated. Thus the improvement is less prominent.

	Pontresina	St. Moritz
Changes compared to the reference map		
Non-forest to forest	614	772
Forest to non-forest	2341	1825
Forest maintained	5797	6398
Non-forest maintained	6084	10724
Changes compared to the original Siegfried Map		
Non-forest to forest	1709	1322
Forest to non-forest	1912	2231
Forest maintained	4702	5785
Non-forest maintained	6513	10381
Sum of deviations from reference changes	3048	1912
Changes compared to the reclassified Siegfried Map		
Non-forest to forest	959	742
Forest to non-forest	2420	2702
Forest maintained	5452	6365
Non-forest maintained	6005	9910
Sum of deviations from reference changes	848	1754

Table 3. Results from land-cover change analysis over both study areas and its improvement through bias correction in the historical map.

5 Discussion

The described fuzzy set based procedure leads to a remarkable improvement of the original historical maps through the removal of classification bias. This approach allows to identify the direction of the bias i.e., forest was found to be underestimated in the original Siegfried Maps. One reason for the underestimation could be that forest, which was the object to be identified, had a lower identification probability than non-forest in the historical mapping. Thus forest had to be enforced during the reclassification process by weighting its fuzzy memberships using threshold-based decision rules. This resulted in an increase of forest area and independently tested accuracy. This gain in accuracy allowed more precise area estimations of the fuzzy classes since different meanings of forest and non-forest memberships were taken into account. This aspect has not been considered yet in recent research where the area of a fuzzy class was considered as a function of the alpha cut level only (Woodcock and Gopal 2000; Fonte and Lodwick 2004). The optimal values of *THR* for reclassifying the fuzzy maps were found to be similar in both test areas and their average provided a strong improvement in both maps (Table 2). If this similarity held for additional study areas, a general applicability of the approach to other regions of similar topographic characteristics could be expected. Thus relationships between uncertainty and topographic predictors (Steele et al. 1998) were shown to be useful for predictive uncertainty modelling and finally for predictive, spatially explicit bias correction.

The model performance depends on the completeness of forest delineation in the Siegfried Map. Where a forest patch is not considered at all in the Siegfried Map, the model is not able to improve, but considers the next (more distant) delineated forest boundary. Therefore, a certain trust in the historical forest cover delineation is required for a proper functioning of the proposed procedure. This minimum quality requirement can be assumed for the Siegfried Map in general. Still, we noticed cases where forest gaps (avalanche tracks, small gaps) were not delineated in the Siegfried Map, which is a limitation of the approach. Furthermore, we need to consider that there are many reasons for uncertainty in maps, which cannot be addressed by such a model. Mainly attribute uncertainty remains unknown.

As could be seen in the example of St. Moritz the classification accuracy can only be improved to a certain degree. Here, the map was less distorted and forest cover was mapped with a higher accuracy (κ = 0.67) since the terrain is easier to access than in Pontresina (κ = 0.55). Topographers could move through this area more easily and better oversee the whole terrain. Thus, the bias is lower, and the gain in accuracy is also lower than in Pontresina. As a result, forest area was even slightly overestimated in some sub-areas of St. Moritz (Table 2).

The application example demonstrated that the procedure allowed for a more accurate forest cover change analysis compared to a reference change (Table 3). The quantitative information provided by the fuzzy sets could thus be directly used for change analyses by evaluating different thresholds used for reclassification. For more sophisticated change analyses the differences in forest definitions, which are used in the maps to be compared, have to be evaluated more carefully. Thus the semantic meaning of forest in the historical maps needs to be investigated to examine the degree of compatibility with definitions in modern maps. Such investigations will need to be linked to historical research since no scientific definitions of forest *per se* existed in the 19th century.

6 Conclusions

This paper contributes to the fields of uncertainty modelling, fuzzy set based spatial operations and land cover change analysis. It presents a model-based approach for correcting inherent uncertainty in land cover maps due to classification bias arising from underestimation of one class. In this approach we linked predictive uncertainty modelling using GLMs to fuzzy set based procedures. After identifying the direction of bias first, bias was then corrected by defining decision rules, which reflected different identification probabilities during the historical mapping. This was done by pixel-wise weighting of forest memberships depending on the uncertainty level at that position. The result was a new crisp map of higher classification accuracy, which also allowed us to perform improved land cover change analyses. The method has been applied to historical forest/non-forest maps, which were derived from the Siegfried Map. Assuming that the results can be confirmed by more study areas, such a procedure could be applicable to other areas of similar topographic characteristics. Thus it overcomes the limitation of recent fuzzy set based approaches where classifications could be evaluated within areas covered by reference maps only (e.g. Binaghi et. al 1999; Jäger and Benz 2000).

The consideration of different meanings of forest and non-forest memberships by weighting them during the reclassification allowed us to compute more accurate area estimates of the fuzzy classes. Thus the approach proposes a further development of estimating the area of fuzzy classes as a function of the alpha cut level only (Woodcock and Gopal 2000; Fonte and Lodwick 2004). If more than one class is evaluated at the same time, the consideration of class-specific meanings results in more reliable area estimates. This is especially true if the classes have different transition characteristics, which can be related to different fuzzy object models presented by Cheng et al. (2001) or if the mapping is object-driven and thus biased.

The procedure makes full use of the quantitative information provided by fuzzy sets. Thus subjectivity, which is inherent in fuzzy sets based on linguistic scales (Power et al. 2001; Woodcock and Gopal 2000), can be circumvented. The gain in accuracy is measurable and the predictive power of the uncertainty model can be tested for different study areas. Thus the approach is suitable for deriving more reliable knowledge of former landscape patterns at larger spatial domains of similar topographic characteristics. Thus it can be used for similar cases of land cover change models. However, it requires detailed and accurate reference maps in calibration areas that allow to train the uncertainty models.

Future research should be dedicated to the development of additional predictors for uncertainty modelling tasks applied to historical maps and alternative decision rules to produce a new corrected historical map based on fuzzy sets. For example, more than two certainty levels could be considered for defining thresholds. The incorporation of more than just two land cover classes would represent an interesting extension of the presented approach. Also, the direct use of weighted fuzzy set memberships for land cover change detection needs to be further investigated. The computation of areas of fuzzy classes, whose memberships have different meanings, needs to be further examined for other application examples.

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