9 Discussion and conclusions

9.1 Introduction

In this thesis I have studied land cover changes in semi-natural Mediterranean areas, especially succession paths and vegetation dynamics following land abandonment. I have shown that land cover change models can be used to analyze, understand and predict the land abandonment process and its consequences. I have also presented methods for the development of a land cover change model. In many semi-natural areas the only source of continuous spatial and temporal validation data are various types of remote sensing data. Therefore I have specially focused on methods to validate the land cover change model using remote sensing data for a Mediterranean ecosystem in the Peyne area, approximately 60 km west of Montpellier, France.

To integrate the land cover change model as far as possible with remote sensing observations for validation, remote sensing data has to be included in an early stage of model development and (transition) rule definition. Therefore, in chapter 4 I started to explore the possibilities of temporal validation and rule definition using time series of aerial photographs. Next, in chapters 5 to 7 I studied conventional and innovative per pixel classification techniques, contextual classification techniques and techniques that use ancillary data to assist the classification. Based on the results of chapters 4 to 7, in chapter 8 I presented a conceptual land cover change model for the Peyne area. Finally, I present the main findings and conclusions of the different chapters in the following sections.

9.2 Validation in time

In chapter 4 I carried out a change detection of vegetation communities over time to determine the location, type and rate of change in the study area. For this, I used a time series of orthorectified aerial photographs from 1946 to 2001. Several environmental and non-environmental factors like distance to roads and urban areas, wetness index, potential radiation, elevation, slope and lithology were found to be important variables for the land abandonment process. Within lithology classes, different transition paths and transition rates were recognised but precise rates of vegetation conversion were difficult to derive from the data because the availability of aerial photographs is limited and does not provide a continuous time series. In recently abandoned fields expected transitions from pioneer vegetation to vegetation higher in the succession, as described by other authors, were only found for a limited number of vegetation/soil combinations within the 55 years covered by this dataset. Moreover, not all lower and middle matorral vegetation types evolve to a climax vegetation of tall matorral. On some degraded and or marginal soils the climax vegetation is a lower or middle matorral vegetation type. In conclusion, important relationships were found to formulate transition rules to predict change of vegetation communities in a land cover change model, but the level of detail that can be obtained in the transition types and rates has consequences for the level of detail in a land cover change model.

9.3 Validation in space

To validate the model results spatially I developed and evaluated several techniques for the classification of spaceborne Landsat 7 ETM+ and ASTER images, and airborne DAIS7915 and HyMap images. The techniques were selected out of the three generally recognized approaches to the classification of remote sensing images: 1) per-pixel based methods like the maximum likelihood classifier. 2) Methods that include data from the spatial domain to analyze imagery. They use not only the per-pixel spectral information but also the spectral information of neighbouring pixels. 3) Methods that incorporate ancillary data into the classification process, which is based on the assumption that vegetation communities are influenced by environmental factors like geology, soil type, soil water availability, elevation, slope, aspect, slope curvature etc.

9.3.1 Per-pixel based methods

The conventional methods like maximum likelihood classification, linear discriminant analysis, K-Nearest Neighbours and the spectral angle mapper perform well as long as there are few classes. As soon as heterogeneous vegetation classes are taken into account the accuracy decreases due to spectral confusion, which is shown in chapter 5, 6 and 7. With increasing number of classes the innovative methods random forests and support vector machines outperformed the conventional classification techniques: these techniques can better derive information from voluminous highly multi-collinear, multi-spectral and hyper-spectral data sets than conventional techniques (chapter 5).

9.3.2 Contextual methods

Although the results of the innovative per-pixel based methods are promising, the classification of heterogeneous vegetation types is still difficult: per-pixel classifiers often result in salt and pepper patterns that are difficult to use for model validation. To overcome these problems it is useful to use context and proximity. Out of many contextual techniques I selected the SPAtial Reclassification Kernel method, because of the promising results in applications other than vegetation classification (chapter 6). SPARK successfully detects vegetation classes which cannot be distinguished at all by conventional per-pixel based methods. All heterogeneous classes show a considerable increase of accuracy but less complex vegetation types show more improvement than more complex vegetation classes. Moreover SPARK proved to be sensitive for the choice of initial land cover and the kernel size. I recommend considering the kernel size as a tuning parameter and to allow the selection of different kernel sizes for different classes in future versions of SPARK.

I also used the concept of proximity in chapter 7: the accuracy of the detection of several classes improved by the inclusion of distance functions: for example the distance to dense matorral is useful to optimise the detection of discontinuous matorral vegetation types.

9.3.3 Methods using ancillary data

Methods that include data from the spatial domain to analyze imagery were studied and evaluated in chapter 5 and chapter 7.

In chapter 5 the innovative methods such as classification trees, random forests and support vector machines proved very suitable for the incorporation of continuous and categorical ancillary data, overall accuracies and accuracies for individual classes improved considerably when many, difficult to separate classes are taken into account.

In chapter 7 I integrated ancillary information and contextual information in a spatio-temporal image classification model: the Ancillary Data Classification Model (ADCM). ADCM accounts for relations between the environmental factors (lithology, geology, water availability, land use history and topography) and vegetation communities. By using these relations the ADCM classification is able to identify heterogeneous vegetation classes much better, proven by an increase of overall accuracy from 29 to 51 %, and by an increase of individual class accuracies: some classes are far better identified by the ADCM than by conventional classifiers.

Except the better classification results, the ancillary data methods also proved to be useful data analysis methods: I used the relationships found in chapter 5 and 7 between environmental factors and vegetation communities in the land cover change model. The land cover change model in chapter 8 is in fact a dynamic spatio-temporal version of the classification model in chapter 7.

9.3.4 Resolution and detection detail

The resolution and the extent of the land cover change model, which in this study is acting on landscape scale is determined by the available remote sensing data. In this study Landsat 7 ETM+ (30 m pixels, 6 bands), ASTER (15-30 m pixels, 9 bands), DAIS7915 (6 m pixels, 79 bands) and HyMap (5 m pixels, 126 bands) are available. Therefore the question arises 'which spatial and spectral resolution performs best?' that I tried to answer in chapter 5. With the statistical per-pixel based methods Landsat 7 ETM+ performed worst. At the challenging 15 class level, the results of the HyMap data are just slightly better than the ASTER data, especially when external data is included, but the extra value is very limited. Therefore I conclude that for 'per-pixel based thematic vegetation classification purposes' the extra value of Hyper-spectral HyMap data with a pixel size of 5m over multi-spectral ASTER data with a pixel size of 15-30 m is only limited. In contrast, contextual methods (chapter 6 and 7) benefit from the higher spatial resolution of HyMap and DAIS7915: overall accuracy of the SPARK classification decreases with increasing kernel size and is optimal with a 3*3 pixels kernel (18 m) If ASTER data is used in SPARK, the minimum kernel size is a 3*3 pixels kernel (45 m) which is too large to describe the vegetation patterns accurately. Similarly the classes that use proximity (discontinuous matorral) in the ADCM classification benefit from the higher resolution because these classes depend on the detection of a pattern of patches of (individual) trees surrounded by lower shrub vegetations.

The number of classes that can be detected in the remote sensing data determines the number of classes to be modelled in the land cover change model. Although all approaches in chapter 5 to 7 produced considerably better results with the detection of many (15 to 18) classes than conventional methods, the results are not suitable for validation of a land cover change model: the producer and user accuracies of some classes are too low. Therefore, in chapter 7 I generalized the 18 class classification into 12 classes for which the producer and user accuracies of individual classes are considerable higher.

Note that an accuracy assessment by using the confusion matrix is a typical per-pixel approach. When spatial components are taken into account, the result should also be checked on spatial pattern reproduction, i.e. how is the coherence of the mapping units and does this match the intuitive notion of field scientists? Visual inspection of the ADCM classification results (chapter 7) and the model results (chapter 8) showed good results with respect to spatial pattern, ecological pattern and coherence of classes. Therefore, more research is needed on methods to quantify these visual evaluations.

9.4 Model building

The results of the temporal validation and rule definition in chapter 4 have several consequences for the development of the land cover change model with respect to succession modelling in recent abandoned fields, the difficulties to derive precise rates of vegetation conversion and the importance of lithology as the main explanatory variable for types and rates of vegetation change.

The spatial validation possibilities of the model results by remote sensing (chapter 5, 6 and 7) also have several consequences for the development of the land cover change model: environmental factors improve the classification, the spatial resolution is determined by the highest resolution of the available remote sensing data (5 m), the number of classes that can be detected (12) determines the maximum model output and the inclusion of neighbourhood information optimises the detection of certain vegetation types.

Based on the constraints and boundary conditions formulated above, which preclude the use of deterministic models, I decided to use the method of 'probability combination' to combine different predicting factors (P-values) for predicting the vegetation cover the most useful approach. This was discussed in detail in chapter 7 and 8. In chapter 8, 'probability combination' allowed me to test several hypotheses about spatial interaction and neighbourhood effects of land use change processes by spatial adjustment of P-values, without the use of a process based model that is difficult or even impossible to parameterize for this study area.

In chapter 8 I showed that the general vegetation transitions in this study area can be assessed by a conceptual model that is not process based. In addition to chapter 4, 5 and 7 I conclude that besides wetness index, solar radiation and lithology also effects of fire and grazing are key factors that explain land cover change of semi-natural Mediterranean vegetation communities. However these key factors do not explain the slow replacement of pioneer vegetations by other vegetations which indicates that abandoned fields are degraded with respect to growing conditions.

I limited the model output to classes that I can detect in HyMap imagery. The interpretation is improved, but the validation is hampered by the fact that small scale variation is difficult to model based on aerial photographs. I conclude that the reconstruction of the initial model situation and modelling of spontaneous patterns is important for future Mediterranean land cover change studies.

Finally, the land cover change model proved to be a valuable tool to test hypotheses in space and time: the spatial interpretation of the difference between model results and observations pointed out which factors were important in addition to the factors that were already included in the initial model.

9.5 Concluding remarks

This study demonstrates that it is possible and useful to develop a land cover change model to test hypotheses about which factors are important in the land cover change process, which can be validated by remote sensing data. However, I conclude that future research should focus on the correct reconstruction of the initial situation from the given remote sensing data and on modelling of spontaneous patterns. The spatial interpretation of the difference between model results and observations point out which factors are important in addition to the factors that were included in the initial model assumptions. It is necessary that the vegetation classes predicted by the model are constrained by the number of classes that can be detected by remote sensing. This thesis shows that the number of classes can be improved by the combination of both spatial and ancillary data. The 'probability combination' approach in chapter 7 is a promising technique for this. Moreover, innovative techniques like random forests and support vector machines also perform well when supplemented by ancillary data: these techniques are definitely worth to be included in common image analysis software packages. Finally, with the increasing use of contextual methods an alternative for the typical per-pixel based confusion matrix should be developed, to quantify the accuracy of pattern reproduction.